UNIVERSITY OF CENTRAL FLORIDA

Multiplex Bionic

Senior Design I Report

Group #17

Arian Garcia

Javier Morales

Tatsiana Smahliuk

Christopher Vendette

Table of Contents

Table of Figures

1 Executive Summary

Prosthetic arms have evolved heavily since their initial inception. Technological advances have allowed for electrically powered prosthetics to gain footing in devices that once relied purely kinematics and mechanical operations. Operated by electromyography (EMG), *Multiplex Bionic* is a bionic prosthetic device that seeks to tackle the number one concern with current advanced powered-prosthesis on the market: cost. Produced for under $700 dollars, this device pinpoints accessibility and ease of use as its key tenants, as well as breaking down the price barrier that exists with many bionics on the market.

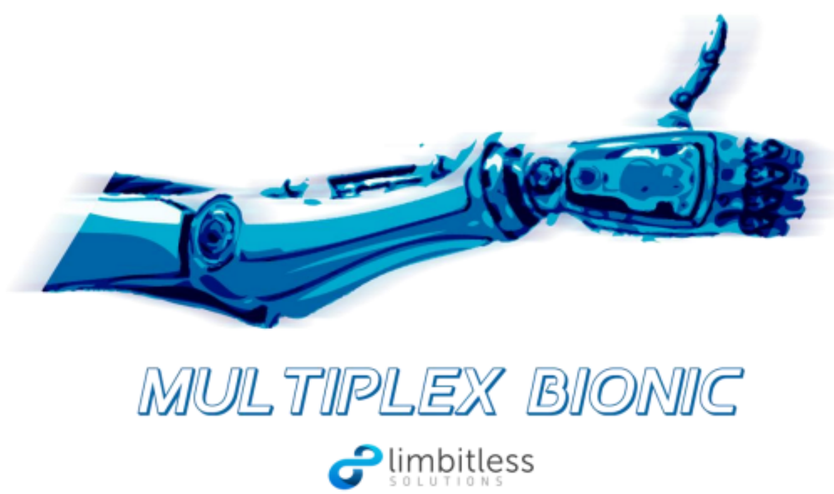
Multiplex Bionic seeks to improve functionality through its use of a number of common gestures/grips. These grips add functionality to the arm and are meant to add to the user's abilities to perform certain actions deemed not possible before. This is a device that is to be geared to be functional for adults with above-elbow amputations. This provides a heavy constraint, limiting the muscle groups which can provide multiple sensor inputs in order to select between the different grip options. Because of this, only one muscle group will be measured with the sensor, but selection will be performed via a selectable button/switch in order to cycle through these grips. Actuation of the fingers is performed by a single muscle flexion by the user.

There are four main components to the system: sensors, controller devices, motors, and power supply. The sensor system used EMG technology to receive the voltage from the user's bicep. This voltage is recorded enable to provide calibration input from the user. After, this calibration is received, the microcontroller will handle the Analog-to-Digital conversion and output signals via Pulse Width Modulation to specific servo motors for them to actuate. These motors represent each finger of the hand, with exception of the last two. Specific programming is performed to ensure that only certain motors actuate when a specific grip is selected such that the correct gesture is performed. The power supply to the system is provided by USB charging via a micro-USB cable to a Lithium-Ion battery. Battery life in bionics remains a key specification, so a low power microcontroller and components will be utilized as much as possible in order to optimize power consumption for the device.

The *Multiplex Bionic* is deemed fully functional when is passes the parameters of being cost effective, long lasting, easy to use, and fulfilling its desired objective. It's objective being able to cycle through different grips and perform actions that would mimic that of the human hand. Many phases of testing will be performed such that this goal is reached. This device will use resources and knowledge provided by Limbitless Solutions to add to their line of affordable powered prosthetic devices. Many that suffer from both congenital and non-congenital forearm amputations are unfortunately limited in their options of advanced bionics due to something as simple as cost alone. This project aims to offer those affected individuals a way to experience enhanced functionality in their life and pave the path towards enhanced self-expression.

2 Project Description

Mutliplex Bionic is a myoelectric bionic prosthetic limb that aims to tackle the issue of different control mechanisms, grips, and gestures for the user all while minimizing cost of production as much as possible. The Multiplex Bionic limb will feature a number of motors that actuate 3-5 grip patterns based on the user's input and selection. Along with this additional functionality, will be improvement in the intuitiveness and functionality of the device.



Group Member	Major	Email
Arian Garcia	Electrical Engineering	aagd@knights.ucf.edu
Javier Morales	Electrical Engineering	javiermorales@knights.ucf.edu
Tatsiana Smahliuk	Electrical Engineering	tatianavus@knights.ucf.edu
Christopher Vendette	Electrical Engineering	cvendette@knights.ucf.edu

Figure 1: Multiplex Bionic Team

This section defines the motivation, goals, requirements/specifications, and constraints pertaining to this project.

2.1 Motivation

In a world that requires functionality, performance, and execution; those who are amputees, those that have lost extremities through injury, or those who are born with congenital absences of limbs carry a heavy burden. Simple tasks transform into strenuous ones, and unknown challenges arrive in different places. The solution seems clear: a bionic answer to a human problem. Advanced bionic limb solutions have been on the market for years, but typically range from prices of thousands to tens of thousands of dollars. Cost is simply too much of an issue, and the price for users is too high.

The *Multiplex Bionic* limb seeks to break down this entry barrier by using 3D printing and other cost-cutting methods to deliver an ambitiously economical product that is donated to the user free of charge. The first generation Bionic Arm from Limbitless Solutions was the first to envision this concept, using techniques that brought the production cost to a sub-$400 level.

The objective of this project is to build on that idea. The purpose of the *Multiplex Bionic Limb* solution is to innovate, redesign this and add functionality to an already existing concept based of feedback from the users and their families. The current, first generation bionic arm consists of an open/close actuation method via the use of EMG electrodes attached to patches on the skin. This is functional for certain tasks, but the human hand does not function as an open/close mechanism.

2.2 Goals and Objectives

This is why the *Multiplex Bionic* limb will consist of a complete redesign of the electronic components as well as adding many accessibility features. These features include, but are not limited to:

- Multiple gesture selection
- “Strap” or “Sleeve” to replace conductive patches
- Decrease in time delay of circuit
- Improved Battery life
- Better calibration methods
- Better gripping methods
- Water Resistance

- Decrease in weight

All of these features have been a result of direct feedback of the user on the previous iteration of the Limbitless arm. Multiple Gesture recognition is the main goal to make the bionic limb more intuitive to the user. Using only 1 input (Bicep or Wrist Flexors), 3-5 motors will actuate corresponding gestures based on the user's selection. This selection process will be performed by the turn of a dial, switch, or knob mounted on the sleeve of the arm itself. A typical example of a programmed gesture includes a “Pincher” mode in which only the motors controlling first finger and thumb are actuating, giving enhanced precision. Other modes include an aesthetically pleasing “Thumbs Up” option, or even a “Mouse Clicking” mode in which the user can operate a computer mouse with the bionic arm. This select ability feature allows for transhumeral amputees to operate multiple digits while still maintaining the functionality for those who suffer from below-elbow amputation.

To further this accessibility, a strap electrode will be designed/used such to eliminate the use of conductive patches. Conductive patches are not ideal because they provide irritation to the skin when removed and must be replaced after each use. The strap electrode will eliminate this issue by providing a method to sense EMG while having the flexibility to take it off at any time without consequence. Adjustability of the strap would provide plasticity to form around each size of arm of the user.

2.3 Requirements and Specifications

Technical specifications are values that are desired in the formation of the product. For this project, there are many parameters that can be improved to provide the user with a more intuitive experience. Below listed are targets that will be attempted to be achieved and/or improved upon.

- Hand gestures: 3-5
- Freedom of movement (Finger Joints): 90 Degrees
- Signal Delay 0.5 seconds
- Cost Range $500-$700
- Weight: Under 3 lbs
- Battery Life: 10 hrs
- USB Charging
- MCU: TI MSP Ultra-Low-Power

For hand gestures/grips, it is important that this project provides an adequate amount of options for the user to utilize. These gestures must be ones that improve upon and increase the daily use of the bionic limb. Signal delay is also another issue, it is essential that the bionic suffers from minimal delay as this would also decrease its' intuitiveness. Low cost is an obvious requirement, as it remains one of the binding constraints of the project, and separates this project from other bionics on the market. Minimal weight is also required such that the project can be used by a multitude of persons with varying degrees of strength. Battery life and USB charging lets the user operate the product for long periods of time whilst having an ease of use, common, method of charging. Use of Texas Instruments MSP430 series of microcontrollers is defined in this project as a high priority. Being that Texas Instruments products serve more complex functions, features, and low-power options, a multitude of microcontroller varieties will be explored, and compared directly with the MSP430 series.

2.4 Constraints

Various constraints need to be identified for this project. These constraints include technical ones, as well as limitations set forth based on feedback from the users. Constraints are defined as a restriction that accurately depicts the projects limitation. There are very many types of constraints that should be considered in the design process. Project level design constraints for a project are defined as follows:

- Economic
- Environment
- Social
- Political
- Ethical
- Health and Safety
- Manufacturability
- Sustainability

Economic constraints are ones that relate to budget, impact economy, and cost. Cost/budget itself is needed to be taken into large consideration. While the parts and components required to realize the design are relatively economical, the overall price of the product must remain under a certain limit. This is to ensure that low manufacturing costs remain a quintessential factor for Limbitless Solutions and their devices. When speaking of economic constraints, it is also important to consider prices of similar products. Because of the niche market, most similar products are sold at a very high cost, allowing for more increase in manufacturing budget. Due to the nature of our product being free, manufacturing costs need to be limited. Most other products of this market can go up to the ranges of thousands of dollars. As detailed in the requirements/specifications section, the cost of this project will be within the range of $500-$700 dollars. This cost constraint forces all of the parts considered to be cost effective, and that the project itself is reproducible in an economical manner.

Environmental Constraints aren't of much worry for this project, as the product is not meant to be disposable. It is important, however, that the product be manufactured in such a way that if damaged, it will not cause significant harm to its surroundings if disposed. This includes selections of different plastic materials, and batteries that can be safely disposed within the environment.

Social Constraints must be examined carefully when dealing with bionics and customized prosthetics. It is important not to design the arm in favor of use with a certain sex/gender/race whether that be fitting requirements or even regards to sensing techniques. Calibration techniques must be implemented such that all usability of the product if available to all. Relative to the weight and size however, some limitations of use might be designated to certain age groups and strength requirements. Trying to minimize the weight as much as possible alleviates some of these issues, but not all. It is essential when examining the outcome of this project, to understand impact it will have on social norms.

Political Constraints designate that the project be done in manner in which the funding is used correctly, efficiently, and without waste. In this project, funding is produced from the non-profit organization, Limbitless Solutions, which receives donations to their cause. It is important that these funds are not misused and all of the funds are used carefully and without waste. This can also be considered an ethical constraint, as described below.

Ethical/Health and Safety Constraints of this project pertain to ensuring that there are no primary concerns during which the product is functional and/or idle. This is can pertain to selection of electronics with low safety risks, and materials which endure heavy shock/impact. It is necessary when selecting components that offer protection circuits and performance standards such that there is a safe backing if any malfunction arrives. The scope of this project, in particular pertains to adults. But it is also important to accept the safety considerations for children, such that if modified in the future, it will be accessible.

Manufacturability Constraints of this project must be determined by first looking at the scope must be considered as an important requisite. Leading constraints in the scope of our design is that the bionic must be functional for both trans-humeral well and below-elbow amputees. This presents a significant challenge, as trans-humeral amputees do not possess flexor muscles required for multiple inputs, and must be taken into heavily consideration. Other scope limitations include the weight of the product due to the increase in motors, leading to the constraint of developing the product for those who have the strength to bear the weight of it. Time is also a limiting factor. Assigned two semesters to complete the research and development of the project means organization and productivity must be valued heavily, and the manufacturability must be clearly defined.

Sustainability Constraints remain a primary concern when dealing with bionic solutions. Accuracy, quality, and practicality are essential to the quality of the product. Main issues with bionics stem from the fact that many applications of the design are just not intuitive. Users, with learned habits, end up purposing their prosthetic for just placeholders as it requires less effort. This is why functionality is the key, and it is a principal condition that the product retains usability in normal life situations. This sustainability pertains to not only the physical quality of the product, but if the user is willing to use it on a routine basis.

2.5 Standards

Engineering standards identify characteristics and practical details that must be met by the system. The idea behind standards is to ensure that minimum performance and safety requirements are met. Standards are written by the experts with knowledge and expertise in the particular field being analyzed. Peripherals to a digital device are subject to technical standards because they can generate their own noise or all the escape of noise generated by the digital devices to which they are connected. Any peripherals to a computer must be authorized by the Federal Communications Commission (FCC). Examples of such peripherals are USB, I^2C, and SPI.

2.6 Funding

The budget is planned to be kept around $500-750. During the manufacturing process additional expenses may occur due to design change and/or additional materials.

This project is sponsored by Limbitless Solutions, a non-profit organization that realizes bionic solutions for kids/adults suffering from congenital and non-congenital limb amputations.

limbitless SOLUTIONS

3 Research

This section of the project report details research conducted into the existing products, technologies, and components necessary to realize this design. Several sections will investigate each of these components, how they work, and the advantages and/or disadvantages if integrated into this project. First, the existing products will be examined, as to provide a system-level overview of what other products are offering in regards to specifications and features. Next, relevant technologies that pertain to the realization of Multiplex Bionic will be examined. Finally, an in-depth view into the strategic components will be realized including the major subsystems of this design.

3.1 Existing Products

It is important to examine existing products and technology and what impact they can on this project. It is essential to realize what components and systems can be integrated into our design. Bionics and prosthetic development, and its advancements are relatively new, so there are many emerging products that utilize different technologies. Some of these products include medical grade devices, as well as devices produced by non-profit organizations.

Even though the design of Multplex Bionic is geared towards using cost-effective solutions, there may be certain components that from high-cost devices that can be implemented in a cost effective manner. Mostly, it is important to evaluate other bionic limbs that are constructed within a similar price range. First, the background of bionic limb technology must be examined, as to realize the improvements within bionic technology that can be utilized.

3.1.1 Background of Bionic Limb Technology

Essential to knowing the advancement and growth pertaining to technology of bionic prosthetics, the history and trend of improvement must be evaluated. Before 600 B.C., ancient Egypt was the home to the very first prosthetics performed as substitutes for missing digits. Crafted from wood and leather, these replacements hardly serviced a need other aesthetic and slight balance adjustments. Moving on to 300 B.C. a bronze limb excavated from Capua, Italy is the first artificial limb to be discovered. Presenting the notion that replacement of prosthetics transcends generations, it is not farfetched to witness substantial innovation in the field. It was not until 1529 where Ambrose Paré offered modern medical procedures presenting a more effective way to perform amputations.

Since this inflection point in history, many gradual attempts have been offered to produce the best prosthetic solutions due to the high volume of amputees.

Pertaining to the loss of arms and upper limb extremities specifically, various methods were used to retain the functionality of the human arm. Methods for grasping small items or performing daily tasks were a challenge. Hooks or grappling methods were widely popular, and a modular socket for different attachments was a prominent solution for those who suffered arm disarticulation throughout the Civil War and onward. Reimagining the upper-limb prosthesis for dynamic actuation of the “hand” presented an entirely different challenge however. Split-hook prosthetics offer a body powered mechanical mechanism to actuate to joined hooks, lending a grip that is powerful enough to grasp small items with precise control. This method was realized in 1812 but is widely used today. Although the innovation in prosthetics is great, this goes to show functionality is the primary concern, and departure from this functionality loses edge in history. Upon the conception of general anesthesia in 1842, the numbers of successful amputations skyrocketed and accordingly so did the demand for prosthetics.

Powered prosthetics are relatively recent, making an appearance in Germany in the early 1900s’. CO_2 and pressurized pneumatic devices offered the first resolution in powered bionics in the late 1940’s, and laid the foundation for research ahead. Research in myoelectric prosthesis occurred around this time as well, performed by Reinhold Reiter. Reiter used vacuum tubes to realize the electrical system due to the absence of the transistor in this portion of history. Using one signal from his muscle he was able to actuate the open and closing of an electric hand. Upon his discoveries there were many technological and medical limitations, and his work was never formally published. As the medical community advanced, and research into electromyography became more pervasive with bionics, subsequently did the size and function of the electronics aside it. Today, the myoelectric bionic arm is the most popular functioning powered prosthetic.

3.1.2 Advancements in the Field

Research in current technological advances in upper-limb bionics is a booming field. Medical, mechanical, electrical, and improvement of materials have resulted in a thriving industry that still faces unique obstacles. The presence of new composites such as carbon fiber and light weight plastics have provided durability and minimization of obstruction into the user’s daily activities.

In regards to sensing technology, Electromyography (EMG) remains the most prominent in the field of bionics. Electromyography signals are electric potentials produced by the body's skeletal muscles. Rectification and filtering of these signals are required to convert them for use. Conductive surface electrodes placed on the surface of the skin detect these myoelectric signals. For more invasive technologies, implanted electrodes remain another option to provide greater information into the neuro pathways left in a patient's residual limb, offering more precision and control.

3.1.3 Modular Prosthetic Limb (MPL)

At the Applied Physics Laboratory located in John Hopkins University, the Modular Prosthetic Limb (MPL) claims to be the most advanced bionic prosthesis in development. This bionic limb can serve as a reference in our project to view the high end specs and future possibilities of prosthesis. The MPL uses a pattern recognition system with a multitude of electrode arrays which relies on the reinnervation of chest muscles that detects algorithms performed by shoulder-level disarticulation and forequarter amputation.

Targeted Muscle Reinnervation (TMR) is a process where nerves contained within an amputees residual limb are transferred to other muscle groups of the body (in this case the chest) to convert an otherwise obsolete function into additional control sites. After this transfer of nerves that otherwise control the hand, wrist and elbow: the new control site serves as biological amplification of the control signals from the reinnverated nerves. The Modular Prosthetic Limb contains over 100 sensors including that of temperature: force, vibrations, and even fine point contact recognition.

To sense muscle potential, the MPL uses two types of implanted intramuscular electrodes, peripheral nerve and cortical electrodes, in conjunction with surface electrodes. Peripheral nerve electrodes detect the activity of nerves outside the brain and spinal cord located within the peripheral nervous system. Cortical electrodes provide information pertaining to the premotor, primary motor, and posterior parietal cortex located which play an essential role in determining planned movements.

Design Parameter	Value
Degrees of Freedom (DOF)	26
Degrees of Control (DOC)	17
Mass (Hand/Wrist)	2.9 lbs
Mass (Upper Arm/Battery)	7.6 lbs
Payload Capacity (Wrist Active)	15 lbs
Payload Capacity (Wrist Static, Upper Arm Active)	35 lbs
Cylindrical Grasp Force	70 lbf
Two-Jaw Chuck Pinch Force	25 lbf
Lateral Key-Pinch Force	25 lbf
Upper Arm Joint Speed	120 deg/s
Hand Open/Close Time	300 ms
Voltage	24 V

Figure 2: MPL Specifications

The MPL encompasses a total of 26 degrees of freedom via the use of 17 motors. Within the bionic arm and hand itself are 21 absolute position sensors, which provide feedback on axial displacement for measurement and training purposes. These are placed mainly at each individual joint, where torque, velocity, and temperature are also measured. The Modular Prosthetic Limb costs up to $500,000 per unit.

3.1.4 Limbitless Solutions Bionic Arm

The bionic arm produced by the non-profit organization, Limbitless Solutions, is a one degree of movement myoelectric-controlled prosthetic limb solution targeted for children with above and below elbow limb disarticulation. The limb operates under the design constrains of noninvasive attachment/sensing, weight, price, and control sites limited to trans humeral amputations. Using 3D printing technology and ABS plastic, the price of the bionic limb remains under 500 dollars, a stark contrast in manufacturing costs compared to other powered prosthesis. ABS plastic is chosen such that the limb remains shock and temperature resistant. Within the joints of the hand is Ninjaflex filament, which provides flexibility and variable movement of the fingers. Wire is strung through each finger/thumb and is tied together to the servo horn of the corresponding MG995 servo motor.

The DC servo motor is operated on a range of 4.8-6 Volts receiving power from a 3.8 Volt nominal voltage lithium ion battery. The voltage from the battery is stepped up using a TPS61090 boost converter for purpose of the Adafruit Pro Trinket (Atmel ATmega328) Microcontroller. The EMG signal is received via the use of adhesive surface electrodes and processed using the Advancer Technologies Muscle Sensor V3 board. The Muscle Sensor board provides full wave rectification and analog smoothing giving a clean EMG signal to the analog input of the microcontroller.

Using EMG snap leads, the signal is received from the user's bicep muscle to and is sent to the sensor board via auxiliary connection. USB charging is performed via the MCP73831 management controller or "back pack" which is mounted to the Adafruit Pro Trinket. This backpack uses two available pins to make use for a switch, which controls the on/off state of the device. Together, these electronics are soldered to through hole proto board and placed in a 3D-printed electronic housing (ECH) along with the servo motor and battery components. This housing is then installed into a plastic sleeve, which is customized for the user based on interests and requests.

This device is produced in a cost effective manner, with manufacturing totaling around $300-$500 dollars total. Our project seeks to replicate a similar cost-effective design, with costs totaling not much more than its predecessor. Many components from the previous Limbitless solutions design are being considered for the Multiplex Bionic, such as similar 3D printing methods, wiring, and micro USB charging.

3.1.5 Exii Bionic Arm(s)

Exii Hackberry: The Exii Hackberry arm is a similar 3D-printed open source bionic limb developed for those who suffer forearm and below-elbow amputations. The Hackberry uses a distance sensor strap in place of EMG to detect muscle contractions. The distance sensor strap contains a TPR-105 IR sensor mounted at the top of a cushion of 5mm thickness. When the user flexes the corresponding muscle, in this case bicep or forearm, the cushion compresses and the change in distance is received by the sensor.

Part	Location	Description	Quantity
ES08MD	Arm	Servo Motor (Small)	2
S03N	Arm	Servo Motor (Large)	1
Arduino Micro	Hand Board	MCU	1
Arduino Micro Shield	Hand Board	MCU Extension	1
MJ-4535-3	Hand Board	Stereo Jack	1
SS-12SDP2	Hand Board	Slide Switch	1
SKRGAQD010	Hand Board	Tactile Button	1
LM2596	Hand Board	DC/DC Converter	1
MJ179PH	Hand Board	PCB Socket	1
TPR-105	Sensor Board	Stereo Jack	1
MJ-4535-3	Sensor Board	Stereo Jack	1
P312-001-RA	Sensor Board	Mini Stereo Cable	1

Figure 3: Exii Hackberry Bill of Materials

The Hackberry contains 3 motors for the thumb and fingers. Located the back of the hand casing itself, is a button that controls the placement of the thumb position from two different states. The first state is a “flat” position in line with the fingers; the second position actuates the thumb at a 90-degree angle. Besides this position change, the thumb does not actuate, only the fingers are activated by the sensor on the user’s muscle.

Exii Handii: Similar to the Hackberry, the Handii is a low-cost prosthetic produced by the Japanese start-up firm Exii. The difference lies in sensory control; the Handii makes use of EMG signals and wireless communication to actuation different gestures on the bionic arm. The EMG sensor is first placed on the user’s forearm muscle; this sensor outputs the signal to the user’s smartphone. Based on the frequency, amplitude, and overall pattern of the signal, the gesture is programmed to actuate the motors corresponding to the control of each individual finger. There are a total of 1 motor per digit, producing 5 servo motors within the Handii bionic arm.

Being that these Exii products are open source, replication of their designs can be easily implemented. Application of the IR sensor is heavily considered, as it doesn’t require the use of gelled electrodes and has an adjustable strap. The individual thumb selection is also an attractive option, as it allows for more options in regards to gestures/grips.

3.1.6 Open Bionics

The U.K. startup Open Bionics produces various robotics along with economical prosthetic hands with manufacturing costs around $300. Open Bionics have realized a selectively differential locking mechanism in their prosthetic hand which selectively locks each digit based on the press of a button from the user. Based on a "Whiffletree" differential design, the mechanically pressed button elongates and fills the corresponding finger hole, restricting the range of motion for the digit. This allows up to 16 total different finger combinations. Whiffletree mechanisms consist of bars connecting different mechanisms. For the Open Bionic prosthetic hand, there are three bars connecting: index to middle, ring to pinky, and a bar to connect the individual bars together.

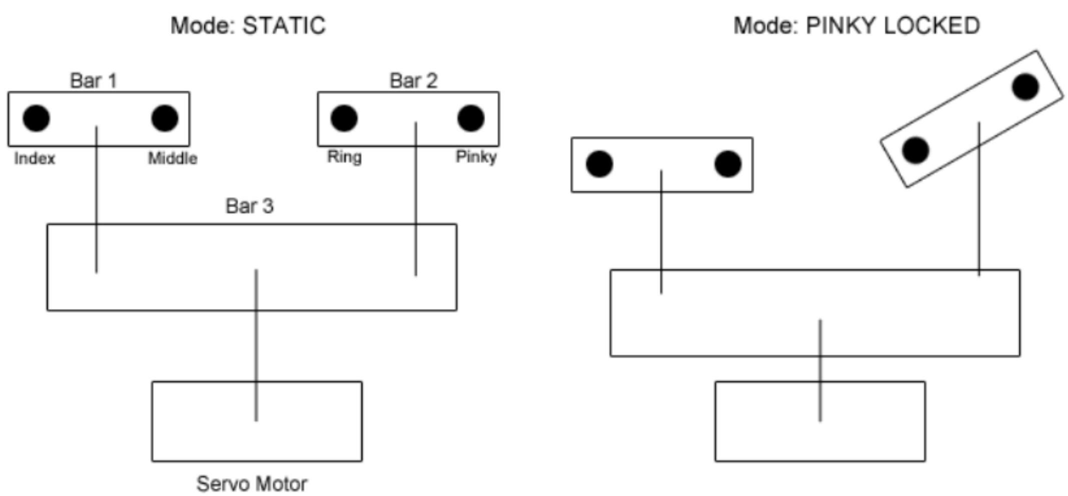


Figure 4: Whiffletree Mechanism

To control the robot hands, Open Bionics uses a servo motor and a low-cost Arduino Micro microcontroller. Using a printed circuit board, the servo motors are connected to the Arduino platform.

3.1.7 bebionic

The bebionic limb is an advanced upper limb powered prosthesis manufactured by Steeper, who offers a range of upper limb prosthetic components. The arm is presented in two different size options for the user: the bebionic small and bebionic large. Dimensions of each these models are listed on the table below.

	Bebionic Small	Bebionic Medium	Bebionic Large
Base (Hand) to Middle Finger	6.5”	7.5”	7.875”
Base (Hand) to Thumb	4.125”	4.875”	4.875”
Chasis Diameter	1.75”	2”	2”
Chasis Width	2.875”	3.125”	4.875”
Palm Circumference	7”	8”	8.625”
Thumb Swing Angle	68 Deg.	68 Deg.	68 Deg.
Weight	390-460g	1.2-1.3 lbs	1.2-1.3 lbs

Figure 5: bebionic Arm Sizing

Powered by myoelectric signals, two surface electrodes, either the ELEC50 (50Hz) or ELEC (60Hz) are used on opposing sides of the inside of the chassis. The bebionic limb offers fourteen different grip pattern for use with daily activities. These different grip patterns offer intuitive function and should be investigated for implementation of the Multiplex Bionic. The 14 different grips are listed as follows:

1. Active Index
2. Column
3. Finger Adduction
4. Finger Point
5. Hook
6. Key
7. Mouse
8. Open Palm
9. Pinch
10. Power
11. Precision Close
12. Precision Open
13. Relaxed Hand
14. Tripod

Active Index grip is also known as a “Trigger” grip is for used with home appliances that require a trigger operating mechanism. With the active index grip, all but the index fingers are actuated while the index finger is remained open. The control then actuates the index to provide grip for household items that require a grip, yet a trigger function such as handhold sprays and power tools.

- Column Grip of the bebionic arm folds the index and middle fingers over the thumb joint. This creates a grip which can activate a button press with precision. This grip can also be used to tap small but lengthy objects, such as car indicators and levers.

- Finger Adduction grip of the bebionic limb is one of the more unique grips on the market. With finger adduction, the digits of the bionic are closed while the thumb lies over, allowing for placement of thin objects such as silverware and toothbrushes.

- Finger Point is one of the more simpler grips offered, and is used for intricate precision when trying to press small buttons such as a doorbell, or keys of a keyboard. In this grip, all of the digits are closed while the index finger remains elongated.

- Hook Grip is a half-closed actuation that is a perfect soluton for carrying bags or lugging items that have handles. This is performed by all of the digits forming a hook by only closing a certain percentage, with the thumb overlaying acting as a locking mechanism.

- Key Grip relies on the closing of the thumb onto the index finger to create a channel for small items to be held with precision. As the name implies, this function can be useful for small, flat items such as keys, credit cards, or thin plates.

- Mouse Grip is a unique option in this series. It allows the user to control the left-click of a computer mouse using the thumb and pinky to grip the object. The index finger is then controlled to click the mouse button.

- Open Palm grip is simply a grip that operates by having all of the digits in thumb in an open state, creating a flat hand. This is useful when trying to hold/carry wide, flat objects such as plates or bowls.

- Pinch Grip includes the execution of only the index and thumb in conjunction, while the other digits remain idle. This grip is utilized in applications where a small object, such as coins, can be lifted.

- Power Grip simply closes all of the digits, creating the best, most powerful grip. This is the most basic grip, and is already incorporated into the Limbitless Solutions bionic hand. This grip can be used when and powerful grip is required, or even a simple handshake.

- Precision Close Grip is similar to pinch grip, where the difference lies in the face that the digits are closed with the actuation. This allows for different options in regards to maneuverability of small objects. The Precision Open Grip is similar, except that the fingers remain open through the entire process.

- Relaxed Hand Grip is simply for visual aesthetic purposes. Relaxed Hand gives the hand a more natural appearance for the user.

- Tripod Grip is similar to pinch grip, except that it incorporates the middle finger into the pinching mechanism as well. This is useful for objects that are too large for the pinch grip, and require more stability.

3.2 Relevant Technology

The most relevant technology in the *Multiplex Bionic* is 3D printing. 3D printing allows the project to be manufactured at a fraction of the cost of today's typical bionic arms. 3D printing is a process of making three dimensional solid objects from a digital file. Instead of using expensive materials like carbon fiber or titanium, 3D-prints are made from different types of plastic. This process makes prosthetics cheap and easy to reproduce. An entire prosthesis can be printed in just 40 hours, which could make them even more desirable.

3.2.1 3D Printing

Additive manufacturing, or 3D printing, is the process used to synthesize three-dimensional objects. Successive layers of material are laid down under computer control to create objects of almost any shape or geometry. Additive manufacturing is what will be used to create the Limbitless arm but the choice still has to be made between the plastic material used, the main two are acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) but there are others such as thermoplastic elastomer (TPE) that are used for special cases.

3.2.1.1 ABS Plastic Filament

Acrylonitrile butadiene styrene plastic filament is very strong, somewhat flexible, and machinable 3D printing material. ABS has a high temperature resistance, which is usually a preferable quality for engineers in professional applications. However, some people are deterred from it because its hot plastic smell and its petroleum based origin. An additional heated print bed is necessary for ABS, which means many printers are simply incapable of printing ABS with reliability. All of these factors make ABS a more expensive option than PLA although it is a stronger more reliable plastic.

3.2.1.2 PLA Plastic Filament

Polylactic acid is not as strong and flexible as ABS but it can have high printing speeds, low layer heights, and sharp printed corners when cooled properly. PLA comes in a variety of colors and translucence and causes low warping on parts. It also has a sweeter smell and comes from plant based origins which make it favorable for hobbyist looking for aesthetically pleasing household items or projects that don't need the higher quality of ABS.

3.2.1.3 TPE Plastic Filament

Thermoplastic elastomer, sometimes called thermoplastic rubber, is a highly flexible plastic that is used much less than the previous two materials. TPE printed objects can be easily squeezed and they will return to their original shape. Many 3D printers have difficulty printing with TPE plastic because its softness can cause extruder jams. Ninjaflex is a popular brand of TPE plastic filament.

3.3 Strategic Components

This section expands upon research into components into the final design. Comparison and investigations of various components is needed to provide a full layout for the Multiplex Bionic Limb. Each sub-section in this portion will denote a major stage component of the project, and how each of these components works in order to be fully integrated.

3.3.1 Motors

Selecting the correct motor is essential to the project. Different types of motors offer tradeoffs in regards to speed, control, weight, holding torque, current draw, as well as a variety of other factors. These factors are essential in a bionic arm which relies on its motors for direct finger actuation. The most common types of motors to be compared are DC, Stepper, and Servo Motors. In order to select the most desirable motor for this project, the specifications of each individual motor must be evaluated. Below are the most common specifications when reviewing motor components.

RPM or Revolutions per Minute is a specification used to evaluate the frequency at which the motor rotates. More specifically, it is the angular velocity at which the shaft of the motor will rotate under no load.

Voltage (Nominal and Range) is essential when selecting a motor for this project. The operating voltage of the motor is usually represented as a nominal voltage which relates to the highest possible efficiency of the motor. Operating a motor outside this voltage usually results in more current draw, poorer heat dissipation, and overall decreased efficiency. A voltage range will often be specified under which the motor can run, but it is most efficient to run it at its nominal voltage.

Torque is a measurement of how much an applied force on an object causes rotation of that object. This can be calculated by multiplying the directional perpendicular distance of the motor with its applied force.

Stall Torque of the motor is the value of torque produced when there is no rotational speed. Stall torque of the motor is the maximum torque the shaft of a motor can provide without rotation. When receiving input from a battery, the motor moves at its fasted speed with no load. When a load is applied to the motor shaft that ceases rotation of the shaft, this produces the maximum stall torque of the motor. At maximum stall torque, the efficiency of the motor decreases drastically: the current draw is elevated and heat is increased. Because of this, it is unadvised to operate motors at stall conditions for more than a matter of seconds.

Power Rating of motors is the largest quantity of power allowed to flow through the input of the motor. This can be calculated using the current under no load and nominal voltage of the motor.

3.3.1.1 DC Motors

Direct Current (DC) Motors have two wire connections, power and ground. After supplying power to a DC motor it will have continuous rotation until that power is removed. Most DC motors run at high revolutions per minute (RPM).

The speed of DC motors is controlled using pulse width modulation (PWM), a technique of rapid pulsing the power on and off. The percentage of time spent cycling the on/off ratio determines the speed of the motor, this is known as the duty cycle. If the motor has a duty cycle of 50%, the power will be on half the time and off the other half of the time. This means the motor will spin at half the speed of a 100% fully on motor. Each pulse occurs so quickly that the motor seems like it is continuously on but just not at full power.

Because of the continuous rotation and high RPM, DC motors are better suited for fans and wheels. In the case of the robotic arm, a DC motor is too powerful and not easily programmable for the use of pulling fingers. DC motors also require a complex design for speed control, and usually an H-Bridge to reverse direction. Current is also an issue, in which a large amount is required to supply any sufficient value of torque as well as gear reduction and altering of gear ratios.

DC motors come in two variations: Brushed and Brushless. The difference lies in the internal operation.

Brushed DC Motors: Brushed DC Motors consist of a commutator (or rotor) armature, brushes, axle, and magnets. The armature is simply coil-wounded wires which activate a two-pole system as an electromagnet. The commutator is a switch which alternates the direction of the current about two times every cycle, pulling and pushing the magnets located on the exterior of the motor. Polarity is switched when the poles of the armature pass those of the magnets and laws of inertia keep the motor rotating in a specified direction. Brushes within the motor keep mechanical pressure against the rotating surface. This can cause friction and unnecessary wear and tear to the internals of the motors.

Brushed DC Motors	
Pros	Cons
Low Cost	Reduction in Torque at High Speeds
Simple Integration	Lower Speed Range
Fixed Speed	Require More Maintenance
Durability	Poor Heat Dissipation

Figure 6: Brushed DC Motors - Pros/Cons

Brushless DC Motors: Brushless DC Motors operate without any mechanical brushes. Unlike brushed motors, brushless motors operate the switching of the polarity electronically instead of mechanically. This is accomplished via a position feedback controller/encoder (servo), Hall effect commutation, or back EMF.

Brushless DC Motors	
Pros	Cons
High Efficiency	High Cost
Low Maintenance Requirements	Difficult to Integrate
Smaller Size	
High Speed Range	
High Output Power	

Figure 7: Brushless DC Motors - Pros/Cons

3.3.1.2 Stepper Motors

A Stepper motor is another variation of a brushless DC motor that operates with a central gear rotor surrounded by multiple electromagnets and rotates in steps. This rotation is achieved by applying current to each of the electromagnets, which attracts the teeth of the corresponding gear shaped rotor. Stepper motors differ from servo motors in that they are positioned without any feedback sensor, operating under an open loop control system. No position encoder therefore is required for stepper motors, making them much cheaper, more, cost-effective, and easier to control the position. The downfall of this however, results in issues arising if the machine loses position as a result of displacement of the internal rotor by foreign object or malfunction due to pushing it past its limits. Because of the lack of a position encoder, there will be no way for the system to know that the stepper is off of position.

This is contrasted with servo motors, in which the position of the servo is read thousands of times per second through feedback and will stop the system if this position is snagged on a foreign object. Stepper motors also lose the ability to drive accurately at higher speeds, and lose a lot of torque quickly as well as the possibility of losing position if driven too fast. This makes stepper motors a good option for low-speed applications, which require unpowered constant holding torque. Speed is essential in this project, and while stepper motors have many appealing capabilities, the performance downfalls result in a less appealing option.

3.3.1.3 Servo Motors

Servo motors are an assembly of a DC motor, a gearing set, a control circuit and a position sensor such as a potentiometer. Servo motors don't rotate continuously like DC motors, instead they are limited to a rotation of 180 degrees. They receive a control signal by way of PWM but instead of RPM the PWM represents the output position. Power is applied to the servo motor until this position is reached which can be determined using a potentiometer. The pulse width of the control signal tells the motor whether to stay at a neutral position or whether to turn clockwise or counterclockwise.

After a servo is commanded to move it must hold that position as well if that is what the control signal is telling it to do. Holding a position means it has to be able to withstand the external forces trying to push the servo back to a neutral position. The maximum amount of force that the servo can withstand while holding its position is its resistive force also known as torque. When looking for the servo that best fits our needs the torque ratio is one of the most important specs because it tells you how powerful the motor is.

Since the position of servo motors can be controlled more precisely than a standard DC motor it makes it a better option for a robotic arm and moving the fingers on that arm. While power is constantly applied to servo motors, its control circuit regulates how much power is drawn to drive the motor. This accuracy in power control is what makes servos beneficial for designs where positioning is an important specification task.

3.3.1.4 Linear Servo Motors

Conventional rotary servo motors are often chosen to drive some type of rotary to linear conversion mechanism which is ultimately connected to the moving payload. However, this rotary to linear conversion mechanism adds inertia, friction, compliance, backlash, and wear, all of which compromise overall system performance and thus reduce motor efficiency. Linear motors, on the other hand, offer the system designer a good alternative in that they produce linear motion directly and therefore eliminate the need for conversion mechanisms such as lead screws, belt drives, and rack & pinions.

A linear motor can be seen as a rotary motor slit down the middle axially and unrolled flat, as seen in the figure below. The same basic technologies used to produce torque in rotary motors are used to produce force in linear motors, such as DC brush, induction, PM brushless, PM stepper, and switched reluctance.

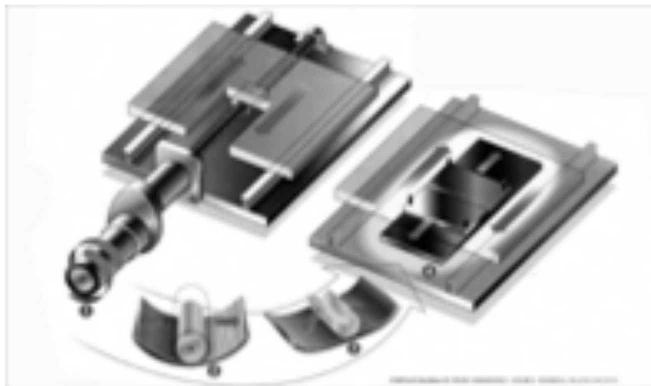


Figure 8: Linear Servo Actuator (*Pending)

Some advantages of linear motors to rotary motors include the fact that linear motors don't have to deal with the added inertia generated from a rotating mechanism. This added inertia can have a parasitic effect on the acceleration of the motor, thus decreasing its max acceleration. Another advantage is the fact that a significant amount of motor torque in rotary servo motors is consumed by the friction and inertia generated. A linear servo motor acts directly on the moving load does more of its force is directly applied to the load which increases efficiency and decreases power loss. Finally, linear motors eliminate some mechanical components found in rotary motors that have a negative effect on the system's stability, settling time, frequency response and bandwidth.

3.3.1.5 Motor Drivers/Controllers

Servo Drive: Many microcontrollers are incapable of providing enough power to motors and attempting to control the servo motors strictly with a microcontroller can lead to damaging or burning out your MCU. In order to provide enough power to servo motors many systems use servo drives.

A servo drive receives a command signal from the MCU, amplifies that signal, and then transmits enough current to the servo motors to produce the desired motion that is proportional to the command signal. Servo motors have sensors on them used as a feedback mechanism to report the actual positioning of the motor back to the drive. This feedback signal in the servo drive is compared to the command signal representing velocity, torque, or position. The voltage frequency and pulse width to the motor is altered to match the command signal and correct any errors in the actual produced output.

Feedback in servo motors allows for precise motor torque, positioning, and velocities to be achieved. This is an advantage when compared to stepper motors because stepper motors are open loop systems. There is no way of the microcontroller knowing if the signal that it sends is the actual output being produced. In a stepper motor system an encoder must be added to achieve this feedback self-correcting procedure in addition to the motor driver needed to supply enough electric current to the motors. This can result in additional hardware that is undesired when the same functions can be achieved with servo motors and servo drivers.

Many drives are available in the market that are compatible with a large variety of motors and aren't motor specific. If the control system is properly configured, the servo motor will rotate at a velocity close to the signal being received by the servo drive. The motor efficiency and performance can be increased by adjusting parameters such as proportional gain, derivative gain, and feedback gain. This process is known as performance tuning.

DC Motor Control using an H-Bridge: If we are to use a DC motor in our project it must be able to rotate in both directions in order for our fingers on the arm to open and close. Without an H-bridge a simple brushless DC motor cannot be programmed to rotate both ways. The reason for this is that the input voltage will always be positive on the motor so we can only turn the motor on or off but not reverse bias the input voltage. The H-bridge allows for this change from positive to negative voltage and thus allows the DC motor to be controlled for clockwise or counterclockwise rotation.

An H-bridge is an electronic circuit that enables the voltage across a load to be applied in either direction (positive and negative). It is commonly used in robotics to allow simple DC motors to run clockwise and counterclockwise. It is essentially four switches that can be controlled and manipulated for whatever action we want to achieve with our motor (see figure and table below). When we look at stepper motors and servomotors they already have H-bridges integrated in them allowing them to run backwards and forwards. When a DC motor needs to be controlled to run in both directions an external H-bridge component must be added to your circuit.

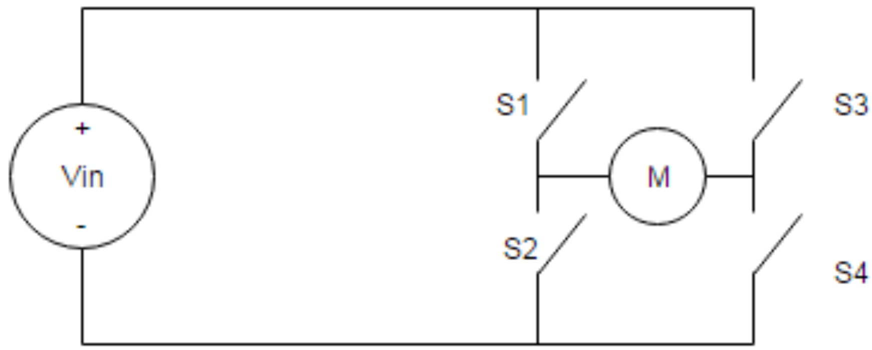


Figure 9: H-Bridge Schematic

S1	S2	S3	S4	Result
1	0	0	1	Motor moves right
0	1	1	0	Motor moves left
0	0	0	0	Motor coasts
0	1	0	1	Motor breaks right
1	0	1	0	Motor breaks left
1	1	0	0	Short circuit
0	0	1	1	Short circuit
1	1	1	1	Short circuit

Figure 10: H-Bridge Switching Mechanism

In the figure and table above we see an H-Bridge schematic along with its truth table for motor control.

H-Bridge Motor Control	
Pros	Cons
Allows implementation DC motors	Additional Components
Controls Direction of motors	No Position feedback

Figure 11: H-Bridge Motor Control - Pros/Cons

Disadvantages: An H-bridge is an additional component having to be added to the circuit when we are dealing with DC motors. Adding components can be a negative since it can make your design more complex, especially when many motors already have H-bridges integrated in them. Another disadvantage of going with an H-bridge controlled DC motor is that there is no position feedback from the motor. Servomotors already have a feedback loop integrated in them that tells the system its exact position and allows the system to correct it for more precise and accurate motor control. In order for our system to know the exact position of a DC motor using an H-bridge we would have to add yet another component called an encoder. The encoder will provide the feedback needed for our motor but essentially we are building a servomotor with several discrete components so maybe it's better to just get a servo to start with.

Advantages: The main advantage of using an H-bridge to control a DC motor is the size and weight that it can reduce on the arm. There are many small and powerful DC motors out there, but it's much harder to find powerful servomotors that aren't too large and hard to fit into the Limbitless arm. If a servomotor that meets the weight and torque requirements that we need is found it would be wise to use it, but until then the small DC motors are very much an option in our design.

3.3.1.6 Encoders

Encoders are used in motors to obtain a digital representation of the angular position of a shaft. Servo motors include already a position encoder to determine the position of the servo at all time. It may be necessary in this project to design an encoder to work in conjunction with a DC motor.

Rotary Encoders: In order to obtain position feedback or rotational speed feedback of a DC motor it is necessary to add an encoder to the system. A rotary encoder converts the angular position or motion of the shaft or axle of a motor into a digital or analog signal. There are two main types of rotary encoders: incremental encoders and absolute encoders.

Incremental encoders: An incremental rotary encoder produces an output that provides information about the motion of the shaft and then that information is further processed to learn about the speed, distance, and position of the motor. It also only outputs pulse signals while a motor is rotating. When using and incremental encoder, the starting position and additional external components are needed to determine the shaft position.

Absolute encoders: An absolute rotary encoder produces an output that provides information on the current position of the shaft, thus making them angle transducers. The output of this type of encoder is a digital signal that corresponds to a certain shaft angle position. The digital signal tells the user the rotation angle position of the motor shaft without the need to count pulses or know the initial position.

For this project, an absolute encoder would be preferred in order to provide feedback for our small DC motors. If we were to go the route of essentially building a servomotor by connecting DC motors, H-bridges, and encoders there are a few routes one could take when looking for an encoder. We could try buying a through-shaft potentiometer, a Hall effect encoder, and even making your own encoder.

In building our own encoder, we would need to purchase a couple of cheap analog IR sensors and a simple gray scale disc or ring. The gradient on the gray scale ring would encode the sine and cosine of the angle while the two IR sensors are positioned 90 degrees apart. This would provide everything that is necessary to determine the absolute angle of a motor shaft. This is a quick low-cost alternative when trying to mimic the functionality of a servomotor but a servomotor itself is not an option.

The problem with all of this is that it would be much tougher to build a more efficient DC motor, which can be controlled to rotate both ways and at the same time provide angular position feedback, than the servomotors in the market. It could take a lot of time and effort away from our group making an encoder ourselves for each motor and combining that with several H-bridges. After that we would have to figure out how to code it to obtain the correct feedback and correction. In our project design it would be much wiser to take the negative of the additional weight that comes from a servomotor as opposed to a small DC motor, because the positives outweigh it. A servomotor off the shelf will likely have a more efficient encoder and H-bridge already integrated in it than we could make ourselves, our job would just be to code the motor drivers correctly to make the motors perform the tasks that are necessary.

Adafruit Motor Shield: In the current design of the Limbitless bionic arm there is no separate controller for the motor. The microcontroller itself controls the motor through its PWM pins. The current design can get away with not having a motor controller because it only has to worry about controlling one motor, therefore only two pins from the MCU will be taken up which are readily available. In the new design of the Limbitless arm we plan on implementing five finger actuation meaning we are using five motors. Five motors cannot be controlled directly from the MCU because there are not enough pins to perform pulse width modulation; therefore we need an extra component such as a motor controller to handle the five motors.

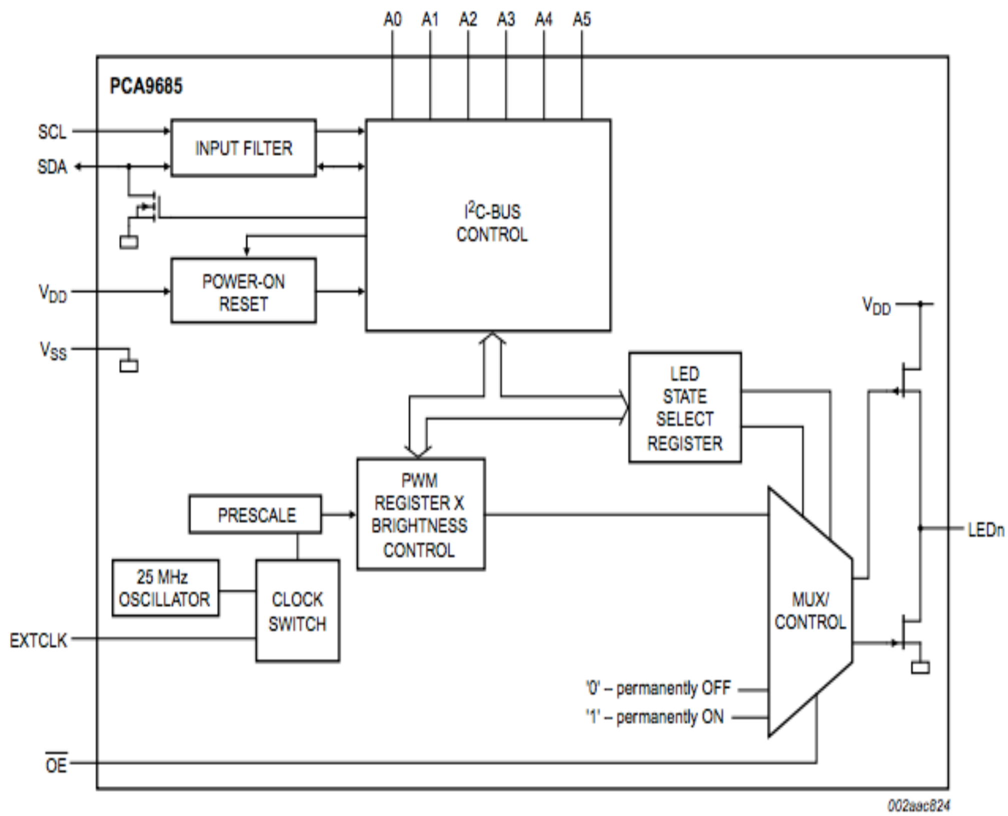


Figure 12: PCA9685 Block Diagram (*Pending NXP Semiconductors)

One option we have in order to control the five motors is using the Adafruit 16-Channel 12-bit PWM/Servo Shield. The block diagram can be seen in the figure above. This servo shield uses just two I2C pins from the microcontroller to control 16 free running PWM outputs. Free running means that we don't have to continuously send a clock signal from the MCU that can tie up the microcontroller because the I2C-controlled PWM driver has a built in clock. Since the I2C pins are a shared bus we can still connect other I2C devices to the pin such as sensors as long as they don't have conflicting addresses.

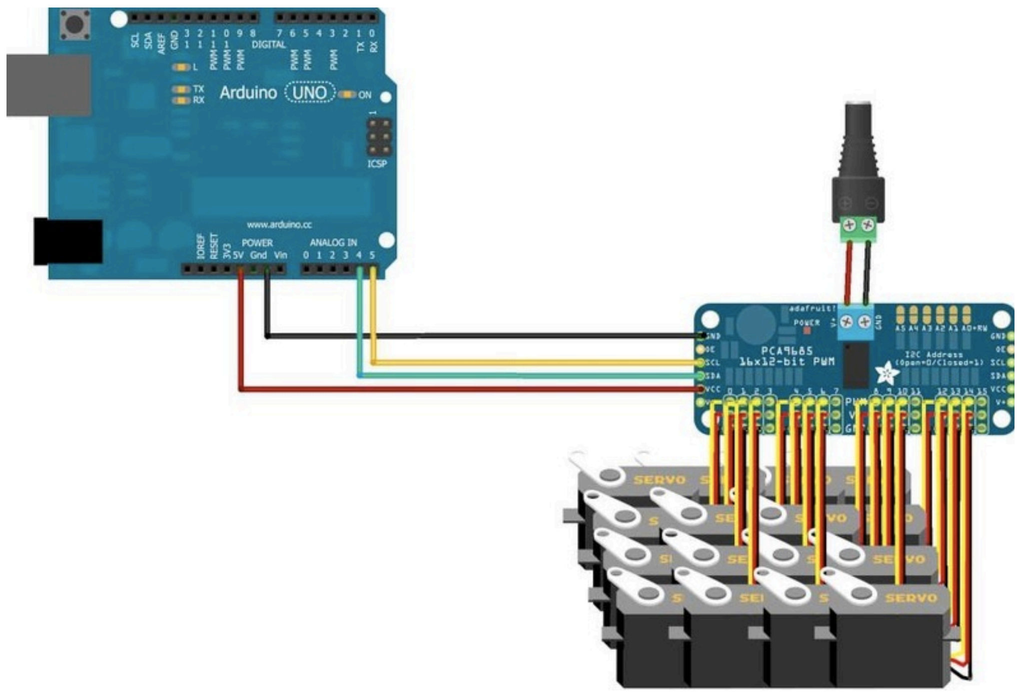


Figure 13: Adding Servos to Adafruit Servo Shield

There are a few net and useful features for us as it pertains to this motor shield. There are three pin connectors in groups of four that allow for up to 16 servos to be plugged in at once (seen in figure above). Obviously for our project we will only need to use a couple of the pin connectors from the motor controller for us to plug in five motors at once. Also, all the output lines are protected by having 220 ohm resistors already connected to them. Finally, if we want to prototype on the board and add extra wiring there is a 5mm x 20mm prototyping area on the motor shield board.

3.3.1.7 Motor Comparisons

The **TowerPro MG995** servo motor is a quite powerful motor and produces a lot of torque, especially for an affordable motor selling for about ten dollars on most sites. While the pros include low cost and high torque, some cons include accuracy and speed. It is very tough to get this specific servo motor to the exact angular position that is desired because it does not center correctly and tends to overshoot.

Figure 14: TowerPro MG995 (*Pending TowerPro)

When combining the poor speed and accuracy of this motor, it becomes a bad option for systems that need very precise motion. However, it is a rather good motor for systems that are willing to sacrifice some accuracy for torque power. Below is a table of the TowerPro MG995 Servo specs.

Modulation	Digital
Torque:	**4.8V:** 130.5 oz-in (9.40 kg-cm) **6.0V:** 152.8 oz-in (11.00 kg-cm)
Speed:	**4.8V:** 0.20 sec/60° **6.0V:** 0.10 sec/60°
Weight:	1.94 oz (55.0 g)
Dimensions:	**Length:** 1.60 in (40.7 mm) **Width:** 0.78 in (19.7 mm) **Height:** 1.69 in (42.9 mm)
Motor Type:	3-pole
Gear Type:	Metal

Figure 15: TowerPro MG995 Servo

This servo motor is the one that is currently being used in Limbitless arms to control all five fingers and allow the hand to open and close its fingers. For the load of the five fingers, a large servo motor with high torque is certainly needed and this motor might even be a good option to control three fingers in our new design.

Tests must be run on each individual finger to see how much torque is needed to make them open and close properly but certainly it is not as much as what all five fingers need to be controlled at the same time with one motor. For this reason, we must look for smaller motors that are still powerful enough to actuate a multiple gesture hand. If we choose to use three TowerPro MG995 servos to control our hand, it might add too much weight to our arm and make it unbearable for someone to carry it around.

HS-85BB Servo Motor: The HS-85BB Servo Motor is a much less powerful motor in terms of torque than the previously discussed TowerPro MG995 servo, but in our application for the Limbitless bionic arm we may have to sacrifice torque for a lighter and more accurate motor. Since the new Limbitless arm is intended to function with multiple gestures, it will also be necessary to use multiple motors. One motor will be used for the thumb, another for the index finger, and finally one for the remaining three fingers. When controlling just one finger, the decreased load might allow us to look for lighter choices that provide less torque but just enough to accurately control the movement of one finger.

Modulation	Analog
Torque:	**4.8V:** 42.0 oz-in (3.02 kg-cm) **6.0V:** 49.0 oz-in (3.53 kg-cm)
Speed:	**4.8V:** 0.16 sec/60° **6.0V:** 0.14 sec/60°
Weight:	0.67 oz (55.0 g)
Dimensions:	**Length:** 1.14 in (29.0 mm) **Width:** 0.51 in (13.0 mm) **Height:** 1.18 in (30.0 mm)
Motor Type:	3-pole
Gear Type:	Metal
Rotation/Support:	Single Bearing

Figure 16: HS-85BB Servo

When we compare the Hitec HS-85BB servo motor to the TowerPro MG995 servo the first thing to notice is the significant decrease in weight and size, more specifically it weighs 66% less. As expected with the much smaller and lighter motor, the torque will significantly decrease as well. In this case when comparing the same two motors, it can be seen that the torque decreases by 68% on par with the weight reduction.

Overall the HS-85BB is a high power motor that features good speed and torque for its size. It is very affordable as it goes for about eight to ten dollars on the market. This motor features high precision centering and is perfect for applications were a standard servo is too heavy or large but you still need the torque of a standard servo.

Futaba S3150 Slim Digital Servo: The Futaba S3150 Slim Digital Servo produces a considerably high amount of torque and speed for a small and light motor. Futaba is generally recognized as one of the top companies in making servo motors, but with this high quality reputation comes the fact that their products are also a bit pricy. These motor are not intended for hobbyists, but for serious projects with larger budgets. The Futaba S3150 servo goes ninety dollars on their website and is probably out of our price change unless we absolutely can't find any other motor that can get the job done. The specs below show why it is such an expensive yet powerful motor.

Modulation	Digital
Torque:	**4.8V:** 51.0 oz-in (3.7 kg-cm) **6.0V:** N/A
Speed:	**4.8V:** 0.24 sec/60° **6.0V:** N/A
Weight:	0.81 oz (23.0 g)
Dimensions:	**Length:** 1.19 in (30.0 mm) **Width:** 0.78 in (11.0 mm) **Height:** 1.13 in (29.0 mm)
Motor Type:	3-pole
Gear Type:	Metal
Rotation/Support:	Double Bearing

Figure 17: Futaba S3150 Slim Digital Servo

This motor is not only small and powerful; it also features digitally enhanced microprocessors that cut the reaction time from transmitter input to servo action in half from their previous models. Other features include a coreless motor and that fact that it is dust and water resistant, which is important when building an arm.

Some of the negatives when analyzing the Futaba S3150 are obviously the price but also the fact that it produces high current draw from our battery. This will result in a much shorter battery life for our system. The reason it has such a high current drain is because it is designed for applications where high torque and high speed are necessary. When looking at it from the stand point of the Limbitless arm, we might not need such a high quality motor that is far out of our budget.

Hitec HS-485HB: The Hitec HS-485HB When comparing the Hitec HS-485HB servo motor with the smaller HS-85BB and the large and powerful TowerPro MG995, one would say that it falls somewhere in between. This motor becomes a very affordable option as it sells for fifteen dollars. The torque of 72 oz-in that it provides should be more than enough to control the load of one or maybe even two fingers on our Limbitless arm. It weighs ten grams less than the TowerPro motor discussed above but produces only a little over half the torque as the MG995.

Modulation	Digital
Torque:	**4.8V:** 72.0 oz-in (3.7 kg-cm) **6.0V:** 89.0 oz-in (6.4 kg-cm)
Speed:	**4.8V:** 0.24 sec/60° **6.0V:** 0.17 sec/60°
Weight:	1.59 oz (45.0 g)
Dimensions:	**Length:** 1.57 in (39.9 mm) **Width:** 0.78 in (19.8 mm) **Height:** 1.49 in (37.9 mm)
Motor Type:	3-pole
Gear Type:	Karbonite
Rotation/Support:	Top Ball Bearing

Figure 18: Hitec HS-485HB Servo

This servo motor is actually the top selling heavy duty servo motor due to its excellent centering, resolution, and affordability. The fact that it is the top selling motor of its type shows that it is used by many people for their projects and has done its job. Finding a motor that is popular can be a great benefit because it will be easier to learn how to program it by finding other similar projects that have been successful.

The main downfall this motor has is that it hasn't been tested with our Ninjaflex and 3D printed fingers, so we don't know if the torque will be enough to accurately and efficiently move and hold our finger joints to the positions we want. It is hard to quantify exactly how much torque is needed for our fingers since it is not a linear quantization, but the best way to find out would by testing different motors to see if their torque and speed is enough while also being accurate and precise with the angle position.

TowerPro MG930: The TowerPro MG930 is an interesting and intriguing option for the servo motor in our arm. We have familiarity with TowerPro servos already since the TowerPro MG995 is currently being used in the Limbitless arm to control all five fingers at once so that is a positive. Essentially this would be a miniature version of that motor since it weighs less than half of the current motor's weight but with that size difference comes less torque of course. We believe that with the decreased load of only handling one finger this motor might be able to work for us. The following table gives us the specs of this motor.

Modulation	Digital
Torque:	**4.8V:** 50.0 oz-in (3.60 kg-cm) **6.0V:** 62.5 oz-in (4.50 kg-cm)
Speed:	**4.8V:** 0.14 sec/60° **6.0V:** 0.11 sec/60°
Weight:	0.92 oz (26.0 g)
Dimensions:	**Length:** 1.43 in (36.2 mm) **Width:** 0.60 in (15.2 mm) **Height:** 1.13 in (28.7 mm)
Rotation:	Dual Bearings
Gear Type:	Metal

Figure 19: TowerPro MG930 Servo

Pololu Low-Power Micro Metal Gearmotor: We considered DC motors as an alternative to servomotors in order to minimize weight and maximize torque. Small micro metal gear motors are very powerful especially for their size. They can produce up to 70 oz-in worth of torque from a very miniscule motor weighing only 10 grams as we can see in the specifications below.

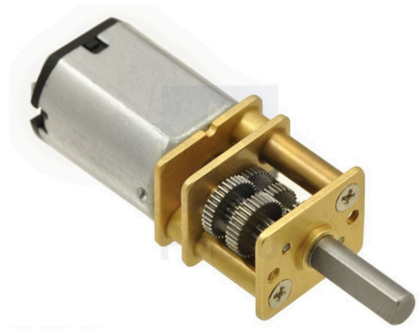


Figure 20: Pololu Motor (Reprinted With Permission from Pololu)

Size:	10 × 12 × 29.5 mm[1]
Weight:	10.5 g
Shaft diameter:	3 mm[2]
Gear ratio	986.41:1
Free-run speed @ 6V:	14 rpm
Free-run current @ 6V:	40 mA
Stall current @ 6V:	360 mA[3]
Stall torque @ 6V:	70 oz·in[3]
Extended motor shaft:	N
Motor type:	0.36A stall @ 6V

Figure 21: Pololu Micro Metal Gear Motor Specifications

If you purchase just one of these motors it will go for about $23 and given it's size and torque we can see why. Although as powerful as the Pololu Low Power 1000:1 Micro Metal Gearmotor may be, this type of DC motor can only start and stop in one direction. In order to rotate this motor clockwise and counterclockwise additional components are needed such as an H-bridge to bias the voltage in both the positive and negative polarities and thus provide bidirectional rotation. On top of the H-bridge, an encoder would be necessary to receive the rotational and positional feedback necessary for precise motor movement. Servomotors have the advantage of already coming with these components integrated in them from the start.

3.3.2 Microcontroller

A Microcontroller, often called an "MCU", is a small computer with a processor and memory that is dedicated to control the functions of a specific system. There are various components of a microcontroller, including: CPU, memory, I/O, timers, serial ports, and analog/digital conversion. Many different specifications determine a type of MCU.

Intel first realized the 8051 family of microcontrollers in the early 1980's for embedded systems application. It utilizes a Complex Instruction Set Computing (CISC) instruction set, which is an instruction set in which includes multi-clock instructions and emphasizes hardware for creating more complex instructions, reducing the number of instructions per program. The 8051 set is an 8-bit wide MCU that totals to 32 cumulative I/O pins, interrupts, serial ports and timers.

The PIC (Peripheral interface controller) family of microcontrollers was developed by Microchip Technology. The PIC MCU comes in three different variations: 8-bit, 16-bit, and 32-bit options. With interfaces including: PWM, LIN, CAN, PSP, Ethernet, I2C, SPI, USB, A/D, UART, and comparators, the PIC encapsulates a wide range of interfaces. PIC microcontrollers excel in low power devices and various applications. PIC uses a Reduced Instruction Set Computing (RISC) instruction set architecture which varies from that of CISC mentioned earlier in that it emphasizes software and operates off of one clock cycle.

The Advanced Virtual RISC (AVR) is a popular choice of MCU's developed by the Atmel Corporation in 1996. Containing an 8-bit architecture, the AVR uses on-chip non-volatile flash memory for storing programs. SRAM, and EEPROM are also integrated on to the chip, allowing programmability without externals.

The Advanced RISC Machines (ARM) is a RISC 32-bit processor heavily used in the industry. MCU's that utilize ARM adhere to a Von Neuman architecture as opposed to the previous mentioned which contain a variation of Harvard architecture. Harvard architecture allocates instruction and data memory separately and are controlled by different buses. The instructions in Harvard architecture are stored in ROM (Read-Only Memory) and data is stored in RAM (Random Access Memory) or registers. Von Neuman, on the other hand, allocates data and instructions to the same memory space, making dynamic compilation possible.

3.3.2.1 MCU Peripherals/Interfaces

Peripherals and interfaces add customizability and functionality, and are an important factor to consider when selecting a microcontroller for this project.

Some of these include UART, SPI, I2C, PWM, Ethernet, CAN, and USB. Based on the complexity and function of design, a proper microcontroller can be selected that utilizes these functions.

UART (Universal Asynchronous Receiver/Transmitter): UART is a component that performs serial communications by taking data bytes and translating the bits individually. Serial transmission is performed either synchronously or asynchronously. Asynchronous transmission is more commonly utilized and is used in UART, whereas USART performs synchronous transmission. Parallel transmission, in contrast with serial transmission operates by sending multiple bits simultaneously on the same path via different channels. The UART performs conversions between these two different types of transmissions. The serial bus transmits date through two wires, requiring devices utilizing serial to have pins for a transmitter (TX) and receiver (RX) For data received from a peripheral device, UART converts serial to parallel and for data from the CPU, it is the opposite, performing parallel to serial conversion. Microcontrollers without UART often control the serial interface directly with the processor. UART also allows capability for control of interrupts via keyboard/mouse and other serial devices. UART is used for various applications such as GPS modules.

SPI (Serial Peripheral Interface): SPI is an interface bus commonly used to send data between microcontrollers and small peripherals such as shift registers, sensors, and Secure Digital cards. It involves a select line, separate clock and data lines that chooses the devices needed to talk to. Primarily it is used in embedded systems. This interface was developed by Motorola and has become an ordinary to use. Using Arduino there are two ways to communicate with SPI. First is by using the shiftIn() and shiftOut() commands. These commands work on groups of pins but are considered slow. Second is the SPI library, which is much faster but will only work on specific pins on the microcontroller.

I2C (Inter-Integrated Circuit): I2C is a communication protocol that allows serial communication over two wires. Using and a “Master” and “Slave” concept, the I2C protocol uses the master to control the clock and generate signals whilst sending/receiving data. The slave adheres to the clock signals laid out by the master, and can only send/receive data to the master, but not other slaves. I2C sends this information through the Serial Data Line (SDA) and Serial Clock Line (SCL) which controls the data and clock, respectively. Different operations of I2C include Multi-Master where there are more than once controlling device connected to the same bus used for more complex applications. I2C offers a way to route all the peripherals to the microcontroller via the use of just 2 wires. These wires are bi-directional and any number of slaves and masters can be connected to these lines.

Pulse Width Modulation (PWM): PWM is a procedure for getting analog outcomes with digital means. Using digital control a signal switched between on and off is created. This on-off pattern can act out voltages in between on (5 volts) and off (0 volts) by altering the section of time the signal spends on versus the time that the signal spends off. The extent of "on time" is called the pulse width. To get fluctuating analog values, you modify, or modulate, that pulse width. If this on-off pattern is repeated fast enough with an LED for example, the outcome is as if the signal is a steady voltage between 0V and 5V controlling the brightness of the LED. PWM is specifically used for servo control of this project. The angle of rotation of the servo is determined by the pulse width but not at all determined by the duty cycle of the signal.

Universal serial bus (USB): USB is an industry standard established in the mid-1990s that defines the cables, connectors, and communication etiquettes used in a bus for connection, communication, and power supply between computer and electronic devices. It is the most popular connection used to connect a computer to devices like digital cameras, hard drives, and smart phones. USB can be used with Windows 98 and above. USB will be used for charging in this project. The cable will consist of USB micro to USB standard. Choosing USB provides accessibility to many charging platforms. USB can connect to computers, monitors, smart televisions, and wall outlets with an adapter.

3.3.2.2 Atmel ATmega 328

The ATmega328 is a high performance, low power 8 bit microcontroller that was used in the original Limbitless bionic arm. This MCU has 6 PWM pins for motor control. This is used on the Adafruit Trinket Pro board sold by Adafruit. This board is used in conjunction with the other components of the Limbitless system to realize the current product. This microcontroller has RISC architecture. For this project, we are switching to Texas Instruments components. Texas Instruments provides a support ecosystem including the e2e community, evaluation modules, and a wide variety of reference designs. Below is the specifications of the ATmega328 for comparison purposes.

Device	ATmega328
Flash (KB)	28
RAM (KB)	2
General Purpose Input/Output	18
ADC 10 Bits	8 channels
Pins	28
PWM	6 channels
Clock Rate	16MHz
Power Regulation	5V
Serial Interface	SPI

Figure 22: ATmega328 Specifications

3.3.2.3 T.I. C2000

The TMS320F28027 is part of the Piccolo family of microcontrollers which provide power like the C28x core attached with highly integrated control peripherals in low pin-count. This microcontroller is code-compatible with previous C28x based code making it highly valuable.

Device	TMS320F28027
Flash (KB)	32
SRAM (KB)	6
SPI	1
ADC 12 Bits	7 channels
Comp_E	1 channel
Timers	3
Instruction Cycle	16.67 ns
SCI	1
External Interrupts	3
Supply Voltage	3.3
I/O	26
Package Type	38 TSSOP

Figure 23: TMS320F28027 Specifications

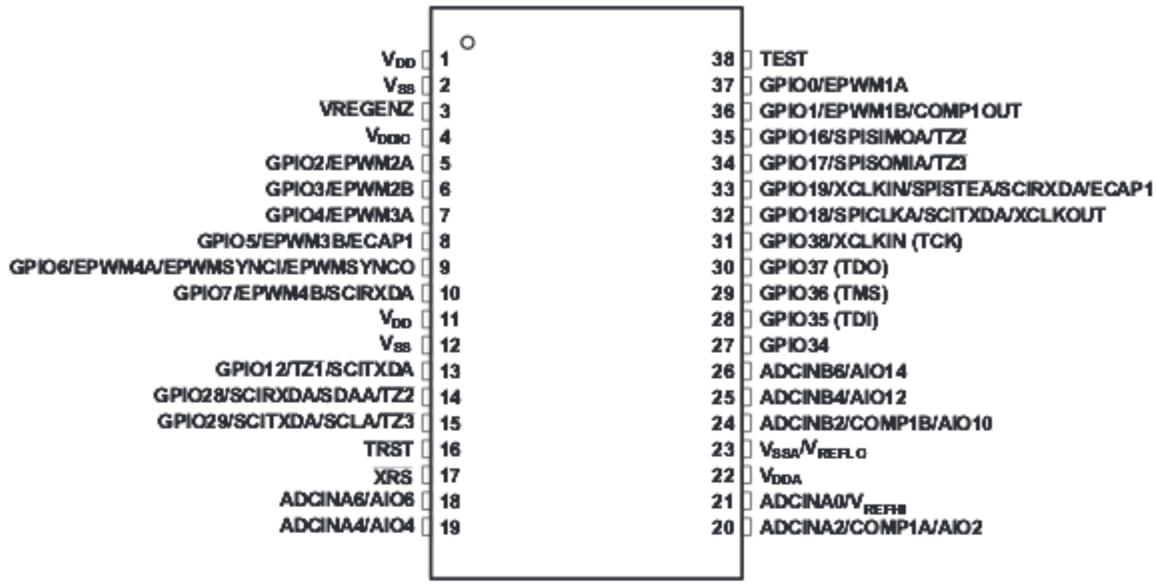


Figure 24: TMS320F28027 Pin Diagram (*Pending Texas Instruments)

3.3.2.4 T.I. MSP430

The Texas Instruments' MSP430 is an industry standard microcontroller option for low power applications. MSP microcontrollers come in 16-bit and 32-bit options with a RISC based architecture. With a maximum of 512kB of flash memory and 64kB RAM, the MSP430 family contains 450+ different MCU's for various applications. The Ultra-Low Power modes available in the MSP430 are achieved by switching on/off various clocks and oscillators. By only enabling the clocks when necessary, the MCU is able to control the overall current consumption.

Another low-power feature is "Instant Wakeup", in which a DCO (Digitally Controlled Oscillator) is programmed to allow the microcontroller to stay in low power modes for a certain length of time. The real time clock within the MCU specifies this time and enables the wakeup at certain periods. The MSP430 family uses FRAM (Ferroelectric Random Access Memory), a non-volatile memory that is similar to that of both SRAM and Flash. Listed below are the different features and specifications of the different product lines within the MSP430 umbrella.

Series	Ultra-Low Power				
Part number	L09x Low Voltage	G2x/i2x	F1x	F2x/F4x	FRxx FRAM
Max Speed (MHZ)	4	16	16	16	24
NVM (max KB)	0	56	120	120	128
SRAM (max KB)	2	4	10	8	2
GPIO	11	4-32	10-48	14-80	17-40
Comparator	⊙	⊙	⊙	⊙	⊙
Timer	⊙	⊙	⊙	⊙	⊙
ADC	⊙	⊙	⊙	⊙	⊙
DAC	⊙		⊙	⊙	
UART		⊙	⊙	⊙	⊙
I^2C		⊙	⊙	⊙	⊙
SPI		⊙	⊙	⊙	⊙
Capacitive touch		⊙			⊙
Multiplier		⊙	⊙	⊙	⊙
DMA			⊙	⊙	⊙
Op amps			⊙	⊙	
LCD				⊙	⊙
RTC				⊙	⊙
PMM					⊙
1.8V I/O					
CRC					⊙
High-resolution timer					
USB					
Hardware Encryption (AES)					⊙
FRAM					⊙

Figure 25: MSP430 Comparison Chart

Developing applications through the MSP430 is done through Code Composer Studio, an integrated development environment (IDE) which functions with all MSP devices. Energia, is another IDE that is supported on several TI devices, which is heavily based on the Arduino platform. Energia offers a wide range of libraries and functions that make creating projects easy and intuitive.

MSP430F147 Microcontrollers: The MSP430F147 is a family of ultra-low-power Texas Instruments' microcontrollers. There are 5 low power modes that are utilized to extend batter life. For this project the low power mode feature is sought out for. This device features a 16-bit CPU, 16 bit registers, and a digitally controlled oscillator which allows wake-up from low power modes to active mode in less than 6 micro seconds.

Device	MSP430F147
Flash (KB)	32
RAM (KB)	1
Multiplier	16x16
ADC 12 Bits	8 Channels
AES	N/A
Timers (16 bit)	2
I^2C	0
SPI	2
Comparators	Yes
BSL	UART
I/O	48
Package Type	64 RTD

Figure 26: MSP430F147 Specifications

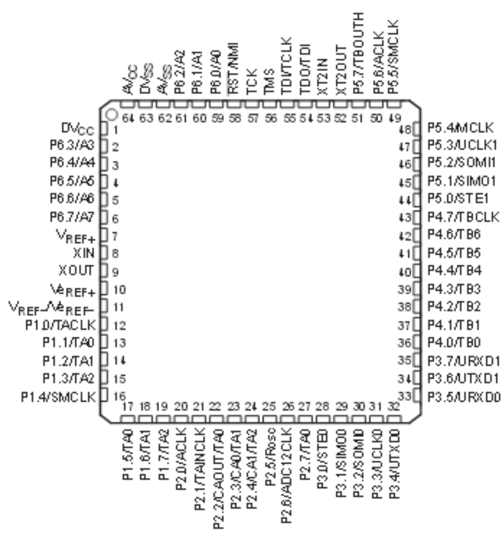


Figure 27: MSP430F147 Pin Diagram (*Pending Texas Instruments)

MSP430FR59xx Mixed-Signal Controllers: The MSP430FR59xx sub-family of the MSP430 microcontrollers offers various features and a wide range of applications including: Wearable electronics, sensor management, data logging, and metering. The FR platform of Texas Instruments MCU's uses FRAM, allowing the speed of static ram (SRAM) and security of flash memory while still preserving ultra-low power (ULP) system architecture. Tradeoffs are apparent between FRAM and SRAM when it comes to power consumption and access speed, in which SRAM can accessed at maximum operative frequency of the device, whereas FRAM limits itself to 8 MHz, and FRAM consumes more power. FRAM gains traction over SRAM in being a non-volatile memory, meaning that it can retain data without a power source. This allows us to have better performance at lowered energy budgets. FRAM is a combination of the rapidity, flexibility, and durability of SRAM with the stability and dependability of flash. This device features 64KB of embedded FRAM (a nonvolatile) memory known for its ultralow power, high durability, and rapid write access.

Device	MSP430FR5969
FRAM (KB)	64
SRAM (KB)	2
Clock System	DCO
ADC 12 Bits	16 ext, 2 channels
Comp_E	16 Channels
Timer_A	3,3 2,2
Timer_B	7
eUSCI A	2
eUSCI B	1
AES	Yes
BSL	UART
I/O	40
Package Type	48 RGZ

Figure 28: MSP430FR5969 Specifications

MSP430FR5969 Pin Descriptions (Left Side)			
Name	**Pin Num.**	**I/O**	**Description**
P1.0/TA0.1/DMAE0/ RTCCLK/A0/C0/VR EF-/ VeREF-	1	I/O	GP I/O with port interrupt and wake up from LPMx.5, TA0 CCR1 capture: CCI1A input, compare: Out1, External DMA trigger, RTC clock calibration output, Analog input A0-ADC, Comparator input C0, Output of negative reference voltage, Input for an external negative reference voltage to the ADC
P1.1/TA0.2/TA1CLK / COUT/A1/C1/VREF +/ VeREF+	2	I/O	GP I/O with port interrupt and wakeup from LPMx.5, TA0 CCR2 capture: CCI2A input, compare: Out2, TA1 input clock, Comparator output, Analog input A1-ADC, Comparator input C1, Output of positive reference voltage, Input for an external positive reference voltage to the ADC
P1.2/TA1.1/TA0CLK / COUT/A2/C2	3	I/O	GP I/O with port interrupt and wakeup from LPMx.5, TA1 CCR1 capture: CCI1A input, compare: Out1, TA0 input clock, Comparator output, Analog input A2-ADC, Comparator input C2
P3.0/A12/C12	4	I/O	GP I/O with port interrupt and wake from LPMx.5, Analog input A12-ADC, Comparator input C12
P3.1/A13/C13	5	I/O	GP I/O with port interrupt and wakeup from LPMx.5, Analog input A13-ADC, Comparator input C13
P3.2/A14/C14	6	I/O	GP I/O with port interrupt and wakeup from LPMx.5, Analog input A14-ADC, Comparator input C14
P3.3/A15/C15	7	I/O	GP I/O with port interrupt and wakeup from LPMx.5, Analog input A15-ADC, Comparator input C15
P4.7	8	I/O	GP I/O with port interrupt and wakeup from LPMx.5
P1.3/TA1.2/UCB0ST E/ A3/C3	9	I/O	GP I/O with port interrupt and wakeup from LPMx.5, TA1 CCR2 capture: CCI2A input, compare: Out2, Slave transmit enable-eUSCI_B0 SPI mode, Analog input A3-ADC, Comparator input C3
P1.4/TB0.1/UCA0ST E/ A4/C4	10	I/O	GP I/O with port interrupt and wakeup from LPMx.5, TB0 CCR1 capture: CCI1A input, compare: Out1, Slave transmit enable – eUSC1_A0 SPI mode, Analog input A4-ADC, Comparator input C4
P1.5/TB0.2/UCA0CL K/ A5/C5	11	I/O	GP I/O with port interrupt and wakeup from LPMx.5, TB0 CCR2 capture: CCI2A input, compare: Out2, Clock signal input-eUSCI_A0 SPI slave mode, Clock signal output-eUSCI_A0 SPI master mode, Analog input A5-ADC, Comparator input C5
PJ.0/TDO/TB0OUTH / SMCLK/SRSCG1/C6	12	I/O	GP I/O, Test data output port, Switch all PWM outputs high impedance input-TB0, SMCLK output, Low-Power Debug: CPU Status Register Bit SCG1, Comparator input C6

Figure 29: MSP430FR5969 Pin Descriptions (Left Side)

MSP430FR5969 Pin Descriptions (Bottom Side)			
Name	**Pin Num.**	**I/O**	**Description**
PJ.1/TDI/TCLK/MCLK/ SRSCG0/C7	13	I/O	General purpose digital I/O, Test data input or test clock input, MCLK output, Low-Power Debug: CPU Status Register Bit SCG0 Comparator input C7
PJ.2/TMS/ACLK/ SROSCOFF/C8	14	I/O	General-purpose digital I/O, Test mode select ACLK output Low-Power Debug: CPU Status Register Bit OSCOFF Comparator input C8
PJ.3/TCK/ SRCPUOFF/C9	15	I/O	General-purpose digital I/O, Test clock Low-Power Debug: CPU Status Register Bit CPUOFF, Comparator input C9
P4.0/A8	16	I/O	General-purpose digital I/O with port interrupt and wakeup from LPMx.5, Analog input A8-ADC
P4.1/A9	17	I/O	General-purpose digital I/O with port interrupt and wakeup from LPMx.5 Analog input A9-ADC
P4.2/A10	18	I/O	General-purpose digital I/O with port interrupt and wakeup from LPMx.5, Analog input A10-ADC
P4.3/A11	19	I/O	General-purpose digital I/O with port interrupt and wakeup from LPMx.5, Analog input A11-ADC
P2.5/TB0.0/UCA1TXD/UCA1SIMO	20	I/O	General-purpose digital I/O with port interrupt and wakeup from LPMx.5 TB0 CCR0 capture: CCI0B input, compare: Out0 Transmit data-eUSCI_A1 UART mode Slave in, master out-eUSCI_A1 mode
P2.6/TB0.1/UCA1RXD/ UCA1SOMI	21	I/O	General-purpose digital I/O with port interrupt and wakeup from LPMx.5, TB0 CCR1 compare: Out1 Receive data-eUSCI_A1 UART mode Slave out, master in-eUSCI_A1 SPI mode
TEST/SBWTCK	22	I	Test mode pin-select digital I/O on JTAG pins Spy-Bi-Wire input clock
$\overline{\text{RST}}$/NMI/SBWTDIO	23	I/O	Reset input active low Nonmaskable interrupt input Spy-Bi-Wire data input/output
P2.0/TB0.6/UCA0TXD/ UCA0SIMO/TB0CLK/ ACLK	24	I/O	General-purpose digital I/O with port interrupt and wakeup from LPMx.5, TB0 CCR6 capture: CCI6B input, compare: Out6, Transmit data-eUSCI_A0, UART mode, BSL Transmit (UART BSL), Slave in, master out-eUSCI_A0 SPI mode, TB0 clock input, ACLK output

Figure 30: MSP430FR5969 Pin Descriptions (Bottom Side)

MSP430FR5969 Pin Descriptions (Right Side)			
Name	**Pin Num.**	**I/O**	**Description**
P2.1/TB0.0/UCA0RXD/ UCA0SOMI/TB0.0	25	I/O	General-purpose digital I/O with port interrupt and wakeup from LPMx.5, TB0 CCR0 capture: CCI0A, compare: Out0, Receive data-eUSCI_A0 UART mode, BSL receive (UART BSL), Slave out, master in-eUSCI_A0 SPI mode, TB0 CCR0 capture: CCI0A input, compare: Out0
P2.2/TB0.2/UCB0CLK	26	I/O	General-purpose digital I/O with port interrupt and wakeup from LPMx.5, TB0 CCR2 compare: Out2, Clock signal input-eUSCI_B0 SPI slave mode, Clock signal output-eUSCI_B0 SPI master mode
P3.4/TB0.3/SMCLK	27	I/O	General-purpose digital I/O with port interrupt and wakeup from LPMx.5, TB0 CCR3 capture: CCI3A input, compare: Out3, SMCLK output
P3.5/TB0.4/COUT	28	I/O	General-purpose digital I/O with port interrupt and wakeup from LPMx.5, TB0 CCR4 capture: CCI4A input, compare:Out4, Comparator output
P3.6/TB0.5	29	I/O	General-purpose digital I/O with port interrupt and wakeup from LPMx.5 TB0 CCR5 capture: CI5A input, compare: Out5
P3.7/TB0.6	30	I/O	General-purpose digital I/O with port interrupt and wakeup from LPMx.5 TB0 CCR6 capture: CCI6A input, compare: Out6
P1.6/TB0.3/UCB0SIMO/UCB0SDA/TA0.0	31	I/O	General-purpose digital I/O with port interrupt and wakeup from LPMx.5, TB0 CCR3 capture: CCI3B input, compare: Out3, Slave in, master out-eUSCI_B0 SPI mode, I^2C data-eUSCI_B0 I^2C mode, BSL Data(I^2C BSL), TA0 CCR0 capture: CCI0A input, compare: Out0
P1.7/TB0.4/UCB0SOMI/UCB0SCL/TA1.0	32	I/O	General-purpose digital I/O with port interrupt and wakeup from LPMx.5, TB0 CCR4 capture: CCI4B input, compare: Out4, Slave out, master in-eUSCI_B0 SPI mode, I^2C clock-eUSCI_B0 I^2C mode, BSL clock (I^2C mode), TA1 CCR0 capture: CCI0A input compare: Out0
P4.4/TB0.5	33	I/O	General-purpose digital I/O with port interrupt and wakeup from LPMx.5, TB0CCR5 capture: CCI5B input, compare: Out5
P4.5	34	I/O	General-purpose digital I/O with port interrupt and wakeup from LPMx.5
P4.6	35	I/O	General-purpose digital I/O with port interrupt and wakeup from LPMx.5
DVSS	36		Digital ground supply

Figure 31: MSP430FR5969 Pin Descriptions (Right Side)

MSP430FR5969 Pin Descriptions (Top Side)			
Name	**Pin Num.**	**I/O**	**Description**
DVCC	37		Digital power supply
P2.7	38	I/O	General-purpose digital I/O with port interrupt and wakeup from LPMx.5
P2.3/TA0.0/UCA1 STE/A6/C10	39	I/O	General-purpose digital I/O with port interrupt and wakeup from LPMx.5 TA0 CCR0 capture: CCI0B input, compare: Out0 Slave transmit enable-eUSCI_A1 SPI mode Analog input A6-ADC Comparator input C10
P2.4/TA1.0/UCA1 CLK/ A7/C11	40	I/O	General-purpose digital I/O with port interrupt and wakeup from LPMx.5 TA1 CCR0 capture: CCI0B input, compare: Out0 Clock signal input-eUSCI_A1 SPI slave mode Clock signal output-eUSCI_A1 master mode Analog input A7-ADC Comparator input C11
AVSS	41		Analog ground supply
PJ.6/HFXIN	42	I/O	General-purpose digital I/O Input for high-frequency crystal oscillator HFXT
PJ.7/HFXOUT	43	I/O	General-purpose digital I/O Output for high-frequency crystal oscillator HFXT
AVSS	44		Analog ground supply
PJ.4/LFXIN	45	I/O	General-purpose digital I/O Input for high-frequency crystal oscillator LFXT
PJ.5/LFXOUT	46	I/O	General-purpose digital I/O Output for high-frequency crystal oscillator LFXT
AVSS	47		Analog ground supply
AVCC	48		Analog power supply
QFN Pad	Pad		QFN package exposed thermal pad. Connection to V_{ss} is recommended

Figure 32: MSP430FR5969 Pin Descriptions (Top Side)

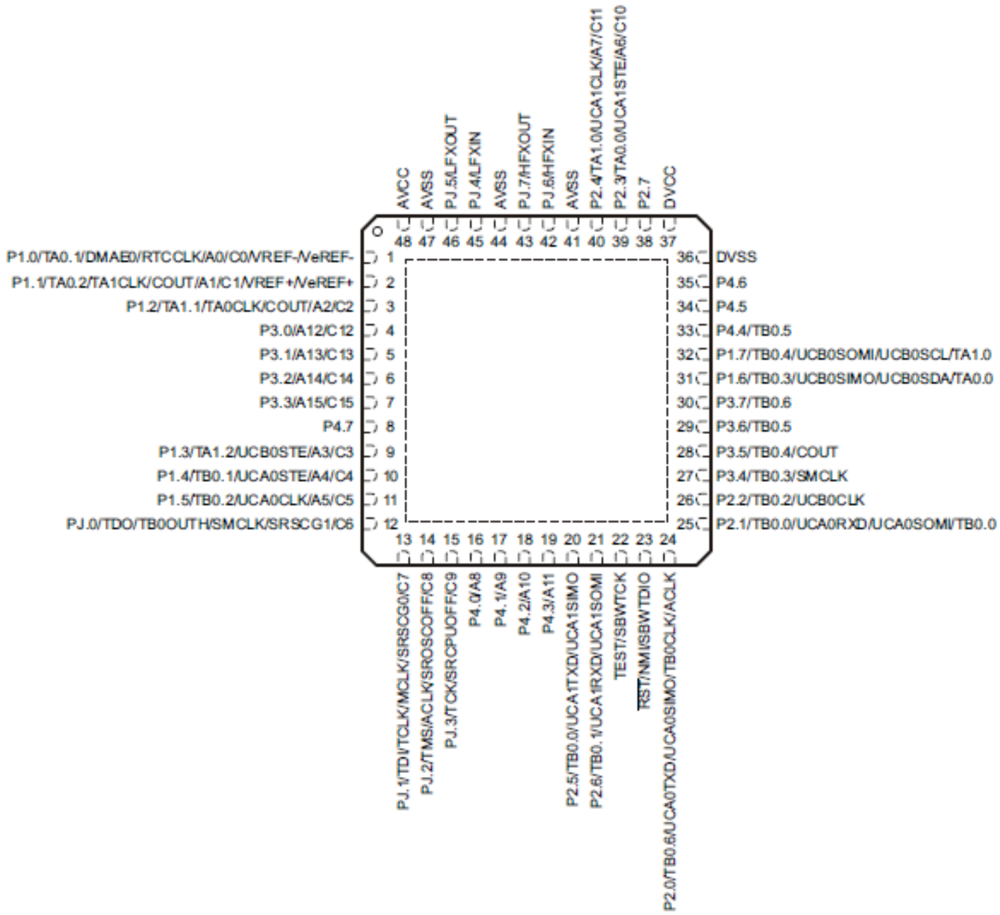
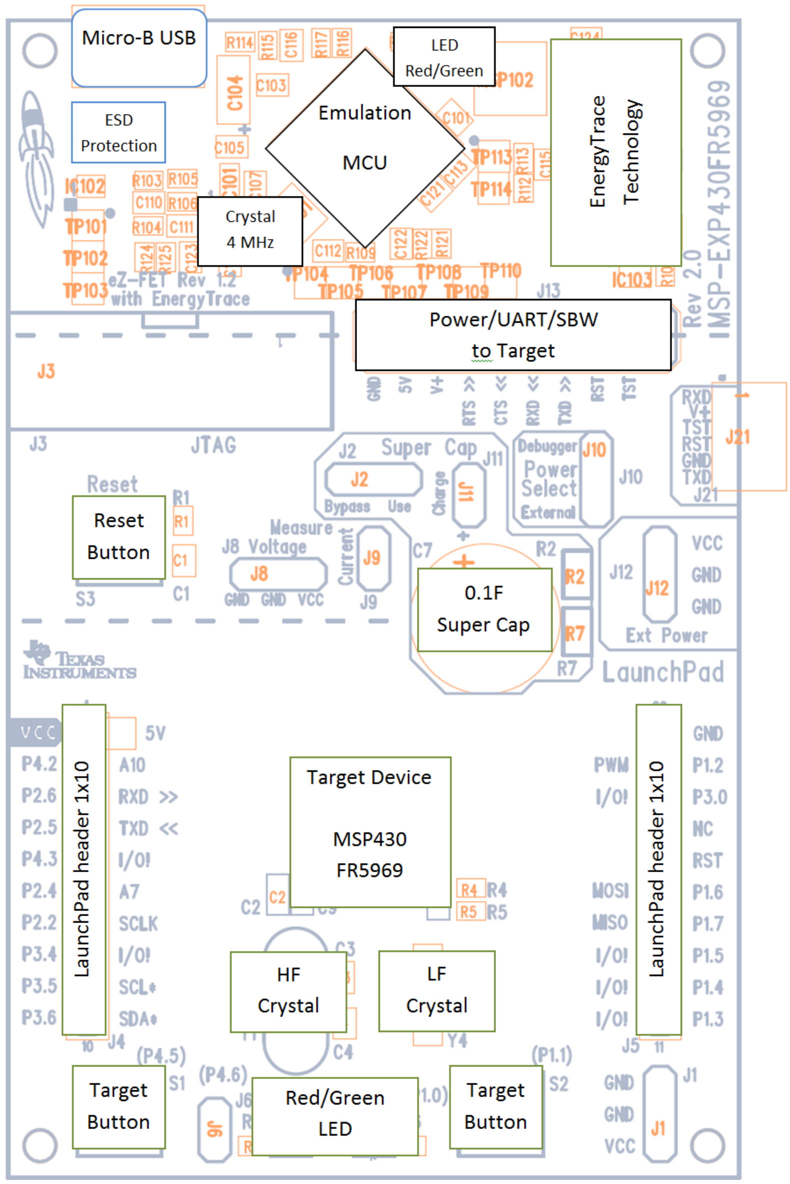


Figure 33: MSP430FR5969 Pin Diagram (*Pending Texas Instruments)

The wide range of low-power applications using the MSP430FR59xx series are achieved through the use of seven low power modes as well as an active mode. The low-power modes, labeled LPM0-LMP4 offer different benefits and include: CPU Off (LPM0), CPU Off (LPM1), Standby (LPM2), Standby (LPM3), Off (LPM4), RTC Only (LPM 3.5), Shutdown With/Without SVS (LPM4.5); The active mode is labeled AM and operates with or without the FRAM on and the use of interrupts can alert the MCU to switch from the seven modes to the active mode.

MSP430FR5969 Evaluation Module: The MSP-EXP430FR5969 is an easy-to-use evaluation module. It allows us to develop on the MSP430 FRAM platform, including on-board emulation for programming, debugging, and energy measurements. This board includes buttons and LEDs for rapid integration of a simple user interface and a super capacitor that allows for standalone applications without external power supply. On the board there is also support for a wide range of BoosterPacks that can quickly add features like graphical displays and wireless connectivity.



MSP-EXP430FR5969	
Pros	**Cons**
0.1F Capacitor for standalone power	7mm x 7mm
Ultra-Low-Power FRAM Technology	Second Biggest Package of Series
7 Microsecond Wakeup Time	

Figure 34: MSP-EXP430FR5969 EVM (*Pending Texas Instruments)

3.3.2.5 Microcontroller Comparisons

In the process of choosing a microcontroller it was decided that the MSP430F147 was to be taken out of the running because it does not have I^2C. I^2C is used to be able to work with the motors of the arm. Choosing between the next two MCUs was determined by memory. The MSP430FR5969 has more memory that retains data without power while the TMS320F28027 has more SRAM and has Flash instead of FRAM. Below are the differences between FRAM and Flash.

	FRAM	Flash
Non-volatile (Retains data w/o power)	Yes	Yes
Write speed (13 KB)	10msec	1 sec
Average active Power (μA/MHz)	100	230
Write endurance	10^{15}	10,000
Soft Errors	Below Measurable Limits	Yes
Bit-wise programmable	Yes	No
Unified Memory	Yes	No

Figure 35: FRAM and Flash Comparison

The table below shows that the TMS320F28027 does not only have Flash instead of FRAM it has a bigger footprint and higher cost, both of which could misfortune the project in the long run. From this analysis the MSP430FR5969 was chosen.

	MSP430FR5969	**TMS320F28027**
Footprint	7mm x 7mm	12.5mm x 8mm
Cost	$5.29	$7.31

Figure 36: MSP430FR5969 and TMS320F28027 Comparison

3.3.3 Sensors

Sensors will be used in this project to retrieve inputs from the user. A sensor is a device that detects and responds to some type of input from the physical environment. The specific input could be light, heat, motion, moisture, pressure, or any one of a great number of other environmental phenomena. Each sensor is based on a conversion of energy from one form to another. The output is generally a signal that is converted to human-readable display at the sensor location or transmitted electronically over a network for reading or further processing. It is important to remember that a sensor provides a measure of physical quantity but not the state.

3.3.3.1 EMG Sensors

The Electromyography Sensor (EMG) can be used to measure the electrical activity of muscles. It is one of the most popular sensors used as a control signal in prosthetic devices. This electrical signal is usually in the order of up to 3,000 micro volts and is referred to as electromyography or EMG.

EMG can be separated into two main groups:

- Intramuscular EMG – performed by inserting an electrode needle into the muscle.

- Surface EMG – performed by placing the electrodes on the skin.

An intramuscular EMG can provide electrical activity of a small number of muscle fibers while surface EMG gives an overview of the electrical activity of muscles near the electrode location. When a muscle contracts, electrical activity is generated within the muscle, which may be measured, using electrodes placed on the surface of the skin in the desired location. Three-lead electrode is used to obtain EMG sensor data: two leads correspond to the common positive and negative voltage and the third lead is a reference/ground lead. Measurements from each of the negative/positive poles are subtracted in the operational amplifiers, thus providing an analog output that can be used for different applications.

When it comes to EMG signals, there are a few types of EMG signals commonly measured:

1. Raw EMG
2. Full-Wave Rectified
3. EMG Envelope

Raw EMG: Raw EMG is the unaltered signal collected which gives the most outputed information. This type of EMG needs at least or above 1kHz sampling rates and requires a large amounts of memory storage. This type of EMG is useful when troubleshooting or trying to determine errors in the EMG signal. This signal, however, it hard to quantify as it is in a form that is very hard to quantify values from. This is why vairous methods of signal processing are implemented to quantify this EMG signal.

Full-Wave Rectified EMG: Full-Wave Rectified EMG simply takes the absolute value of the EMG signal. This is done electronically by using a full-wave rectifier and is mainly used before another step.

EMG Envelope: EMG envelope requires the Full-Wave Rectified EMG followed by a low-pass filter. When doing this electronically it adds a slight delay, and because of the reduced freqency the sampling rate is lower. This type of EMG is very easy to interpret and detects muscle activity at a surface level. This type of signal is very useful as a control signal and is used to control many different projects. For this project, a sufficient EMG envelope will be implemented

Sensors: There are two types of surface electrodes are commonly used:

- Dry electrodes;
- Gelled electrodes.

Dry electrodes are in direct contact with skin and usually have the pre-amplifier circuitry at the electrode site thus making them hevier and more difficult to fixate. Average weight is around 20g.

Gelled electrodes use an electrolytic gel as a chemical interface between the skin and the metallic part of the electrode. Gelled electrodes can either be disposable or reusable. Disposable electrodes are the most common since they are very light (around 1g). They come in a wide assortment of shapes and sizes, and the materials.

3.3.3.2 EMG Sensor Comparison

Delsys: High-performance surface EMG sensors with wired and wireless technologies. Sensors feature single differential and double differential models that don't require any skin preparation. They are convinient and easy to use and don't irritate skin like sensors with gelled electrodes. Delsys EMG sensors provide very good signal quality and stability. All sensor models share unique input characteristics that guarantee low-noise signals and hassle-free recordings.

Parameter	Value
Preamplifier Gain	10 VN ± 1%
Bandwidth	Open
Noise	1.2 uV (RMS, R.T.I.)
CMRR (6/10 Hz)	-92 dB (typical)
Power Consumption	20 mW (typical)
Input Impedance	>10^{15} Ω/0.2 pF
Temperature Range	0 – 40 °C

Figure 37: Delsys Sensor Specifications

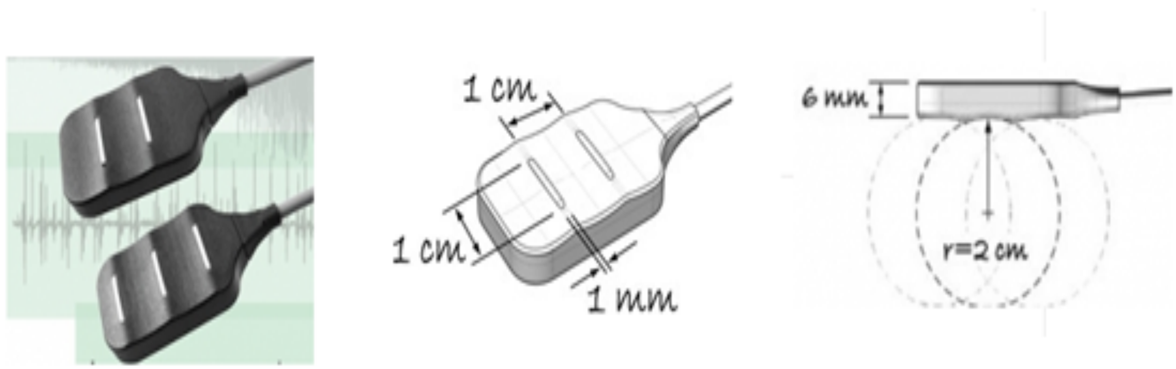
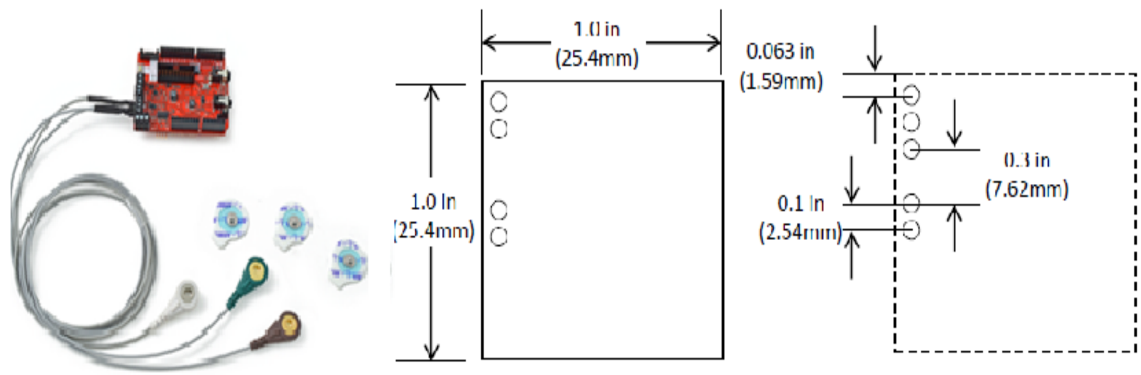


Figure 38: Delsys EMG Sensor (Reprinted with Permission from Delsys)

Advancer Technologies provides low-cost and simple to use muscle sensor kits. Sensors feature small form factor, adjustable gain, and on-board 3.5mm cable port. Pins fit on standard breadboards which makes prototyping and testing very easy and convinient. Advancer's muscle sensor is designed to be used directly with a microcontroller and don't provide a raw EMG signal. The output signal is amplified, rectified, and smoothed, therefore, it works well with a microcontroller's analog-to-digital converter. Three gelled electrodes are used with this sensor and, therefore, skin preparation is necessary for a better signal.



Parameter	Min	Typical	Max
Power Supply Voltage	± 3.5 V	± 5 V	± 18 V
Gain Setting, Gain = 207*(X/1 kΩ)	0.01 Ω (0.002x)	50 kΩ (10,350x)	100 kΩ (20,700x)
Output Signal Voltage (rectified)	0 V	--	+ Vs
Differential Input Voltage	0 mV	2-5 mV	+Vs/Gain

Figure 39: Advancer EMG Sensor (*Pending) and Specifications

MyoWare EMG Sensor: The MyoWare EMG sensor is a muscle sensor offered by Advancer Technologies. This sensor performs by allowing the electrodes to be attached to the EMG board itself, with the ground breaking out into its own separate cable. This is the latest version of the advancer technologies EMG sensor and provides the best rectifying and smoothing EMG signal necessary for the microcontroller's analog-to-digital converter. The MyoWare EMG Sensor is capable of capturing raw EMG data as well as the EMG linear envelope. The EMG envelope is a result of full-wave rectification and passing the signal through a low pass filter, which makes result more useful for analysis and interpretation.

The MyoWare EMG sensor offers a multitude of other features. Besides being able to output two different types of EMG data, the MyoWare muscle sensor can operate off of a single supply and be connected to development boards directly which support 5V. Along with this feature, the muscle sensor also has on-board LED indicators for power and control indication. An ON/OFF switch is also included on the board to control the operating state of the device. The MyoWare EMG sensor is currently being implemented in the Limbitless product line because of these features.

Figure 40: MyoWare Muscle Sensor (*Pending Advancer Technologies)

EMG Circuit Stages: There are seven main stages in any EMG circuitry. Depending on application it is possible to have several parallel lines but each of them has to include these components.

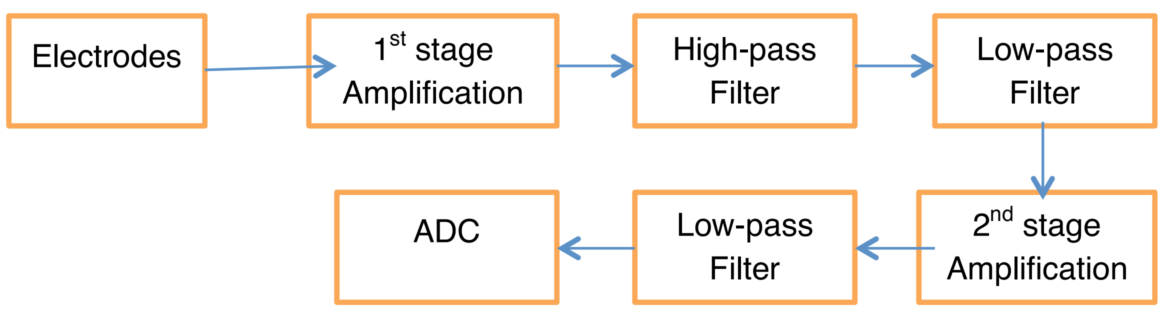


Figure 41: EMG Sensor Signal Processing

EMG Signal Acquisition is achieved in several stages. First stage is using differential amplification technique. The differential amplifier must have high input impedance and very low output impedance. Differential amplification is achieved with the help of an instrumentation amplifier for high input impedance.

The instrumentation amplifier carries out differential amplification by subtracting the electrode input voltages V1 and V2. The noise signal common at V1 and V2 is eliminated. A small gain of 5 or 6 is recommended for signal acquisition. Further amplification will be done in other stages.

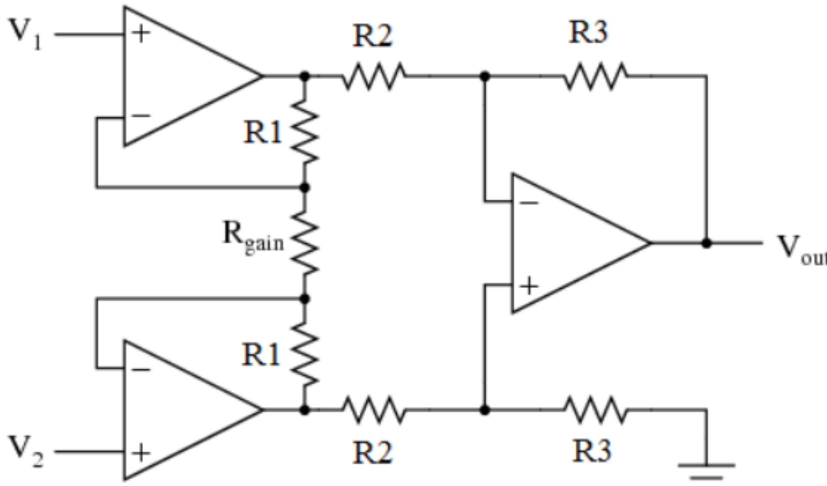


Figure 42: EMG - First Stage Amplification

$$\text{Gain} = \left(1 + \frac{2R1}{Rgain}\right) * \frac{R3}{R2}$$

Vout = (V2 - V1)* Gain

The output from the pre-amplifier is processed by a high-pass and a low-pass filter before entering into the second amplification stage that amplifies signals again to attain an expected gain. The second amplification stage is an inverting amplifier and its gain can easily be adjusted by choosing different resistors. The low-pass filter follows the second amplification stage. Finally, the output signal from the amplification and filtering circuit is fed into an analog-digital converter (ADC). The amplitude of EMG signals is very weak (in the order of tens to thousands μV), so the necessary gain of the amplifiers used in EMG applications is in the range from 1000 to 10000.

EMG filtering circuitry has both, high-pass and low-pass filters. Filters are used after the first and second amplification stages. The noises and the EMG signals are simultaneously amplified and this is not favorable for the following process so filtering hat to be used after each amplification stage. The corner frequency, the roll-off rate, and the circuit topology have to be chosen to design a filter. The order of a filter determines the roll-off rate of the filter. The first order filter has a roll-off rate of -6dB/octave while a second order filter has -12dB/Octave.

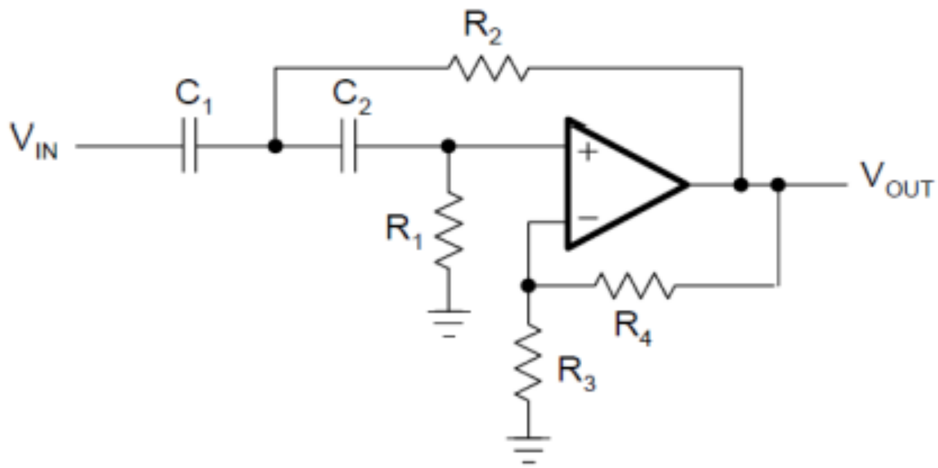


Figure 43: EMG - First Order High-Pass Filter

There are several types of noises with different characteristics within the low frequency components. Therefore, the design a high-pass filter is more complicated comparing with low-pass filter design.

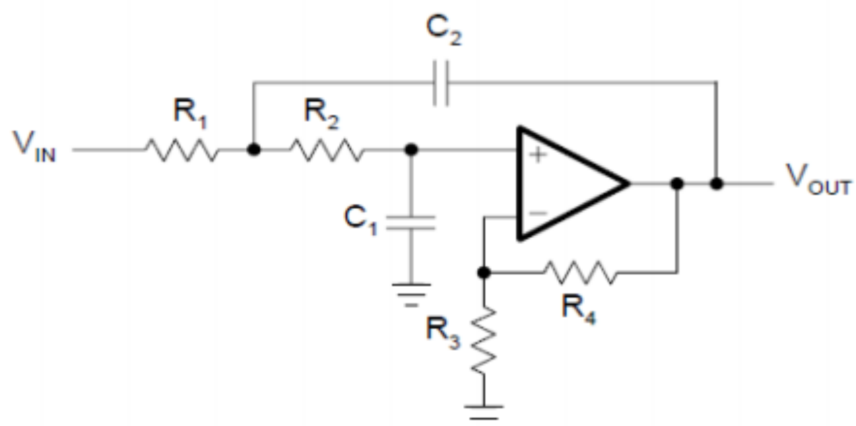


Figure 44: EMG- Second Order Low-Pass Filter

Higher order filters are usually constructed by cascading first- and second-order blocks and they provide more precise filtering, therefore, design of higher order filter is always preferred.

EMG Control is very important in order to be able to successfully achieve all functions implemented in robotic prosthesis. Effective control technique is absolutely necessary when it comes to driving the electric motors in the bionic arm. Implementing the desired control of motors is achieved by converting the analog amplified EMG signal into digital format. After this, the motors are driven with the help of a microcontroller through the thresholding technique.

EMG analog-to-digital conversion is a necessary step in order to be able to control the motor. While converting an EMG signal into digital format, three specifications should be taken into account:

- Quantization - number of bits in digital format in which an analog signal can be converted into by an ADC. The number of quantization bits determines the resolution of the ADC. The higher the number of quantization bits, the less resolution of the ADC we will get. Twelve-bit converters with a resolution of 4096 discrete levels are commonly used, but 16 bits are popular as well.

- Range of conversion – the maximum amount of voltage an ADC can convert into digital quantized bits. The ADC range setting should match the analog output voltage of the EMG system of ±5 V. Smaller range would increase overall signal precision, but must be used carefully to assure that ADC input will not go into saturation. The gain selection is determined by the amplitude range of the input signals (±20 μV to ±2 mV) and the desired system output signal range. The best choice is to amplify the EMG signal so that it doesn't exceed ±5 V. Gain should be chosen for a specific site of measurement and can have a range of 1000 – 10,000.

- Sampling rate - number of samples an ADC can convert in one second. It is determined by the highest frequency component in the signal and the required time resolution. It should be kept very large so that the data loss of EMG is at a minimum. The sampling frequency is required to be of at least 5 - 10 times the highest frequency component of the signal.

Pattern recognition can be used to compare the EMG signals obtained with the prototype EMG signals to distinguish different hand gestures. A hand gesture, implemented in this project, can be defined as motion that can be used for non-verbal communication or a physical activity necessary for completing a certain task. A primary goal of gesture recognition is to create a system which can identify specific gestures and use them to convey information or for device control such as prosthetic. Depending on the number of signal patterns to be classified and number of EMG inputs, the accuracy ranges between 88 and 99.75%.

The location of the EMG sensors is very important for certain type of gestures as different hand and finger movements are controlled by the different muscle groups on the forearm. Therefore, the EMG sensors must be placed on the related muscle groups responsible for the fingers in order to classify individual finger gestures. Most of the muscles that move the wrist, hand, and fingers are located in the forearm. It means that pattern recognition will only be feasible for individuals with fully developed/functional forearm.

The success of the EMG signal classification depends on three stages: pre-processing, feature selection and classification. Important factors include but not limited to

- Intensity of muscle contraction
- Timing of muscle contraction
- Position of the electrode
- Surface preparation
- Electrode properties
- Quality of contact between the electrode and the skin.

Training is always required when it comes to EMG pattern recognition. Any gesture has a starting and ending point that can be determined my numerous testing and data acquisition. However, it differs among individuals so there is no uniform pattern. Each case has to be studied independently to determine the variation in EMG signals for a specific hand gesture. Training may also have to be repeated for an individual when signal activity changes due to the regression of muscle tissue which is common for certain health conditions.

Quality of EMG signal can also be affected by different noises:

- Ambient noise: arises due to electromagnetic radiation and impossible to prevent;

- Inherent noise in electrical equipment that can be prevented by using high quality electronics;

- Instability of motors used in the device can unpredictably change the amplitude of EMG signal.

Noise should always be minimized and it is hard to achieve when using multiple EMG inputs that are required for quality pattern recognition. Different studies showed that 8 EMG inputs will provide sufficient data for pattern recognition assuming that all factors and conditions described above are taken into consideration.

EMG Testing is an important part of evaluating the system. There are quite a few software packages that may be used. However, manual muscle test should always be performed to ensure that there is an actual signal and that electrodes are placed over the desired muscle group. Pre-trial session should be recorded first to check the EMG signal and to get the subject used to the setup and instrumentation. This trial session should be documented. Post-trial session may also be recorded to compare results with pre-trial and experimental results to check the accuracy of the performed experiment and software performance.

ACQKNOWLEDGE offers complete EMG analysis and recording solution automated with EMG analysis routines and dozens of other automated analysis routines and transformation tools. Here are some examples of tools that are offered:

- EMG Frequency and Power Analysis
- Locate Muscle Activation
- Derive Average Rectified EMG
- Derive Integrated EMG
- Derive Root Mean Square EMG

EMG Frequency and Power Analysis is the tool kit that is required for this project. It extracts several measures derived from the power spectrum of an EMG signal. The EMG signal is split up into a fixed number of time periods and the power spectrum is computed using the Power Spectral Density transformation.

Measures analyzed for each channel of data:

- Median Frequency
- Mean Frequency
- Peak Frequency
- Mean Power
- Total Power

Additional Tools for Recording EMG in the MRI allow to record EMG data in the MRI by adding on specialized MRI Smart Amplifiers. The EMG100C-MRI amplifier and cable/filter set allow for cleaner data recordings in the MRI environment.

EMG Analysis software by *Motion Lab Systems* is another software package for consideration. It offers a wide range of powerful analysis methods using Fast Fourier Transform (FFT) techniques as well as many traditional EMG analysis methods making it especially suitable for educational as well as research uses. The data can be processed and exported to third-party applications for additional analysis via C3D files or standard ASCII formatted files compatible with Excel, SAS and MATLAB etc.

Basic features:

- EMG Graphing
- EMG Analysis
- EMG Trial Reports
- EMG Analysis Reports and Methods

This is the one of the most powerful and easy to use software packages using FFT analysis that is available to the clinicians and researchers. The program reads EMG data directly from C3D files as well as the native file formats from BITIS, Motion Analysis Corporation, Vicon Motion Systems. Written for the Kinesiologist driven environment, this software effortlessly delivers instant viewing and full color reports using sophisticated Frequency Spectrum, Power Spectrum and Muscle Correlation techniques.

Electrical safety is required when working with EMG equipment. EMG has to be insulated from the power line and all accessible parts must be connected to the ground. The electrical hazard for the patient is generally caused by faults in the grounding system. A leakage current of sufficient intensity trough the cardiac region may cause ventricular fibrillation. Isolated amplifiers are a preferred choice when designing EMG system. In isolated amplifiers all connections are electrically isolated from the power line and ground connections. It makes a dangerous leakage current highly improbable. Optical isolation is used; it allows conversion of the neurophysiological voltages into an optical signal. The optical signal is then transmitted across the isolation barrier and reconverted to voltage. The maximum current which leaks to earth should not exceed 10 mA at 50 Hz in normal circumstances. The leakage current should be checked and recorded at regular intervals by authorized personnel. Any contact between a second power-line-operated apparatus and a patient connected to the EMG machine should be avoided for safety reasons and also for reduction of noise and artefacts.

For safety reasons the circuit should never be connected to a human's body (via EMG electrodes) unless it is powered only from batteries and completely disconnected from any power supplies that are plugged into the wall.

3.3.3.2 EEG Sensors

Electroencephalography is a medical imaging technique that reads scalp electrical activity generated by brain structures. When brain cells (neurons) are activated, local current flows are produced. Brain electrical current consists mostly of Na+, K+, Ca++, and Cl- ions that are pumped through channels in neuron membranes in the direction governed by membrane potential. EEG measures voltage fluctuations resulting from ionic current within the neurons of the brain. The EEG records brain's electrical activity by placing several pairs of electrodes on a patient's head. These electrodes are disks that conduct electrical activity, capture it from the brain and convey it out through a wire to a machine that amplifies the signal. Scientists attach electrodes in pairs on the head because they're measuring the difference in voltage between the pair. Electroencephalographic reading is a completely non-invasive procedure that can be applied repeatedly to patients, normal adults, and children with virtually no risk or limitation. It can assist in the diagnosis of a variety of neurological problems, from the common headache to seizure disorders, strokes and degenerative brain disease.

Figure 45: NeuroSky EEG Sensor (*Pending NeuroSky)

NeuroSky's EEG biosensor digitizes and amplifies raw analog brain signals (raw EEG is at 512Hz) to deliver concise inputs to games, toys, and devices running health and wellness, educational and research applications. EEG biosensors feature direct connection to dry electrode, one EEG channel with reference and ground, extremely low-level signal detection, and advanced filter with high noise immunity. NeuroSky offers a multitude of EEG sensing products, which can detect within the micro-Volt range. The technologies within these sensors is called "Brain-Computer Interface" (BCI) technology which operates by monitoring direct electrical impulses with a sensor attached to the forehead. Patented algorithms within the device itself are used to interpret these received signals are are outputted digitally to an electronic device.

Dimensions

- Size: 2.79cm x 1.52cm x 0.25cm
- Weight (Max) 130mg

Specifications

- 512Hz sampling rate
- 3-100Hz frequency range
- ESD Protection: 4kV Contact Discharge; 8kV Air
- Max Power Consumption: 15mA @ 3.3V • Operating voltage 2.97 ~3.63V
- UART (Serial):
- – 1200, 9600, 57600 baud
- – 8-bits
- – No parity
- 1 stop bit

Figure 46: NeuroSky EEG Sensor Specifications (*Pending)

3.3.3.3 IR Sensors

An infrared sensor is an electronic instrument, which is used to sense certain characteristics of its surroundings by either emitting and/or detecting infrared radiation. Infrared sensors are also capable of measuring the heat being emitted by an object and detecting motion. They work by using a specific light sensor to detect a select light wavelength in the IR spectrum. When an object is close to the sensor, the light from the LED bounces off the object and into the light sensor. This results in change of the intensity that can be detected using a threshold. The IR light is transformed into an electric current, and that can be detected by a voltage or amperage detector.

A pair of IR LEDs can be used as motion detectors. The first IR LED is wired to emit LED and the second LED is wired to transmit a signal when it receives an IR input. When an object is within range of the emitted IR, it reflects the IR back to the receiving LED and produces a signal. This signal can be then used for different applications.

Infrared sensors are broadly classified into two main types:

- Thermal infrared sensors – use infrared energy as heat. Their photo sensitivity is independent of the wavelength being detected. Thermal detectors do not require cooling but do have slow response times and low detection capabilities.

- Quantum infrared sensors – provide higher detection performance and faster response speed. Their photo sensitivity is dependent on wavelength. Quantum detectors have to be cooled in order to obtain accurate measurements.

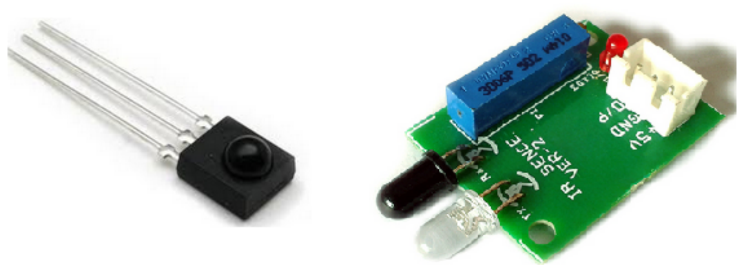


Figure 47: IR Sensor (*Pending)

3.3.3.4 Pressure Sensors

A pressure sensor is a device, which senses pressure and converts it into an analog electric signal whose magnitude depends upon the pressure applied. Pressure sensors are commonly referred to as pressure transducers, pressure transmitters, pressure indicators or pressure switches.

Pressure measurement can either be relative to a reference value or on an absolute scale.

- Absolute Pressure Measurement: Absolute pressure sensors have limited usage because it is impossible to attain a state of perfect vacuum. Sensors based on absolute pressure measurement require strict specifications for precise outputs.

- Differential Pressure Measurement: In differential pressure measurement, pressures of two distinct positions are compared. These types of measurements are used for feed pressure monitoring purposes.

- Gauge Pressure Measurement: It a subtype of differential pressure measurement where we compare pressure at any point to the current atmospheric pressure. There is no consistency in gauge pressure measurements because atmospheric pressure does vary with altitude and hence its applications are limited to non-critical measurements.

Electromechanical pressure sensors convert the applied pressure to an electrical signal. A wide variety of materials and technologies has been used in these devices, resulting in performance vs. cost tradeoffs and suitability for applications. The electrical output signal also provides a variety of choices for various applications.

LPS25H: The LPS25H is an ultra-compact absolute piezoresistive pressure sensor. It includes a monolithic sensing element and an IC interface able to take the information from the sensing element and to provide a digital signal to the output. Sensor features low power consumption (4 μA to 25 μA), embedded 24-bit ADC, selectable ODR (1 Hz to 25 Hz), and high shock survivability (10,000 g).

The complete measurement chain is composed by a low-noise amplifier which converts the resistance unbalancing of the MEMS sensors (pressure and temperature) into an analog voltage that is available to the user by an analog-to-digital converter. The pressure and temperature data may be accessed through an I^2C/SPI interface thus making the device suitable for direct interfacing with a microcontroller. The LPS25H features a Data-Ready signal which indicates when a new set of measured pressure and temperature data are available thus simplifying data synchronization in the digital system that uses the device.

Vdd = 2.5 V, T = 25 °C, unless otherwise noted

Symbol	Parameter	Test Condition	Min	Typ	Max	Unit
Vdd	Supply voltage		1.7		3.6	V
Vdd_Io	IO supply voltage		1.7		3.6	V
Idd	Supply current @ ODR 1 Hz, highest resolution			25		μA
IddPdn	Supply current in power-down mode, T = 25 °C			0.5		μA

Figure 48: LpS25H Pressure Sensor Specifications

3.3.3.5 Position Sensors

Position sensors are widely used in robotics to sense and control the arm movement. The most popular can be divided into three groups:

- Potentiometers
- Encoders
- Resolvers

Potentiometers are the analog devices that translate rotary or linear motion into a change in resistance. In potentiometer one terminal is connected to a voltage source, second to the ground, and the third connects a sliding contact called a wiper. When the wiper moves across the resistive track, the voltage will change, corresponding to the new position. This voltage change can be used to control anything from volume or light intensity to the movement of complex mechanical systems. When only two terminals are used (one side and the wiper), a potentiometer acts as a variable resistor or rheostat. Potentiometers work as a voltage divider. The wiper divides the voltage of the resistive element into two parts. The position of the wiper can be found by measuring obtained voltage.

Encoders are used for converting the angular or linear displacement into the digital signals. Incremental encoders are positional feedback devices used in robots that provide incremental counts. Each mechanical position is unique and the count is only incremented when new position is compared to the previous one. Incremental Encoder is versatile and can fit a wide variety of applications. The three broad categories of applications based on environment are heavy duty, industrial duty, and light duty (servo). The most common type of incremental encoder uses two output channels A and B to sense position. The two code tracks with sectors are positioned 90° out of phase and the two output channels of the encoder indicate position and direction of rotation.

Some types of encoders are:

- Linear encoders: used to calculate the directions and positions that are in the linear form. Example: Linear motors.

- Rotary encoders: help to calculate the directions and positions that are in the angular form. Examples: Motor.

- Incremental encoders: used in robots for sensing the position from its last position.

- Absolute encoders: bring a definite position that is proportional to a fixed reference position.

Dynapar Series E9 miniature encoder is a super-compact modular encoder for small servo and stepper motor feedback. It features Integrated ASIC for enhanced reliability and accuracy with up to 512 PPR resolutions.

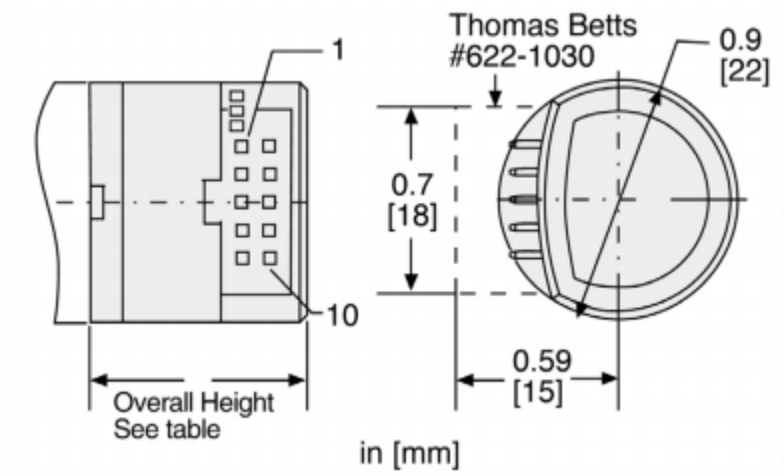


Figure 49: Dynapar E9 Encoder Dimensions (*Pending Dynapar)

Weight: 0.15 oz. (4.14 g)
Operating temperature: -20 ℃ – 100 ℃

Electrical Specifications:

Parameter	Min	Typical	Max	Unit
Supply Voltage		5 ± 10%		V DC
Supply Current		10		mA
Output Voltage	2.5			V
Output Current		6 (25 ℃), 4 (100 ℃)		mA
Frequency Response		200		kHz
Termination		5 pin header or flying leads		

Figure 50: Dynapar E9 Electrical Specifications

Resolvers are rotary electrical transformers that implemented for calculating the degrees of rotation. They require only AC signal and the output signal of a resolver is proportional to the angle of rotating element with respect to the fixed element. The resolver has a stator with a pair of windings and a rotor with one winding. The sinusoidal electric current excites the rotor winding, and the electromagnetic induction makes the current to pass through the stator windings. This process generates a cosine and sine feedback current with the stator windings, which are fixed at 90 degrees. The magnitudes of currents are measured to find out the angle of the rotor that is proportional to the stator windings.

3.3.3.6 Conductive Materials

Piezo-Resistive Materials are the materials that tend to have an increasing resistance across distance and are great for making potentiometers and location sensors. Piezo-resistive fabrics are often also resistive across distance (x,y) but have a resistance that decreases under pressure (mechanical stress) through the material (z). These materials are great for making pressure, bend and often stretch sensors. There are a range of resistive fabrics available on the market, often sold for anti-static and electromagnetic field (EMF) shielding purposes.

Conductive textiles can be made with metal strands woven into the construction of the textile. Conductive fibers consist of a non-conductive or less conductive material, which is coated or embedded with electrically conductive elements, often carbon, nickel, copper, gold, silver, or titanium. Substrates typically include cotton, polyester, nylon, and stainless steel to high performance fibers such as aramids and PBO. The performance of technical textiles depends on type of fiber material, configuration, and assembly structure. There are various kinds of fibers, which are selectively used according to the requirement of particular applications.

The volume, surface resistivity, and conductivity can be expressed by equations:

$\rho v = R\ (\Omega) \times RCF \times t\ (cm)$
$\rho s = R\ (\Omega) \times RCF$
$\sigma = 1/\rho v$

RCF is the resistivity correction factor; $R(\Omega) = V/I$ - fabric resistance.

Parameters	Temp	RH	Fibre Resistivity	
Material	Degrees Celsius	Percentage	Resistivity (Fabric)	Resistivity (Yarn)
Polyurethane	18-20	47	(10.6±0.5)E5	(10.0±1.1)E5
Cotton	17-19	56-61	(2.23±0.17)E6	(2.10±0.19)E6
Wool	14-16	63-66	(2.1±0.5)E6	(2.0±0.1)E6
55% Wool 45% PET	14-16	78-82	(10.6±1.7)E6	(10.8±0.3)E6
67% Cotton 33% PET	14-16	72-75	(10.8±1.5)E6	(10.1±1.3)E6
Basalt	18-25	60-65	(10.6±0.5)E11	(2±0.5)E6
Stainless Steel	20-25	75-78		6.9E-7
Copper	20-25	75-79		1.68E-8
Polyester	17-23	69-74	(1.8±1.5)E33	(1.8±1.5)E31

Figure 51: Resistivity of Various Fabrics

3.3.4 Power

Powering the arm efficiently is one of the most essential portions of this project. As stated before, lack of battery life drastically reduces the ease of use for bionics. In order to make sure the bionic arm is powered successfully, the correct battery must be chosen, and adequate supply voltages within range must be distributed to all of the components. Charging the battery and the circuit required is also a portion of the project needed to be taken into heavy consideration. The following section will investigate these essential components required to power the system, such that the correct ones can be selected to increase efficiency.

3.3.4.1 Battery

Selection of the battery serves as an essential function in this project. Battery life is an important feature that dictates the success of the product and most portable devices. For bionics in particular it is essential to keep the product charged for long periods of time so that it retains its intuitive properties to the user. Batteries operate by converting chemical energy using oxidation-reduction reactions into stored electrical energy that could be utilized by a system. The battery is composed of two terminals: a negative anode, a positive cathode, and an operating medium in between: an electrolyte. The electrolyte functions as a channel in between these two terminals that permits the flow of electrical charge. Most batteries are characterized by the tradeoff of power and energy, in which they are specified as having a clear advantage in one or the other. There are many different form factors, figures of merits, and specifications to recognize when selecting the correct battery.

Voltage: The first of these parameters to consider is the voltage. When classifying a battery, it is important to consider the nominal cell voltage and cut-off voltage. The nominal voltage is the voltage of a fully charged battery when distributing a rated capacity at a specified discharge rate. Nominal voltage is also referred to as "Mid-Point Voltage" or (MPV), and is defined as the voltage of a cell when one-half of the total energy of the battery has been discharged. This can be found as the mid-point on the charge/discharge curve which plots cell voltage versus time.

Battery	Nominal Voltage
Alkaline	1.5V
Nickel-Metal Hydride	1.2V
Lead-Acid	2V
Lithium Polymer	3.3V, 3.7V
Lithium Ion	3.6V, 3.7V

Figure 52: Nominal Voltage of Popular Secondary Batteries

End of Discharge Voltage: The End of Discharge voltage (EOD), final voltage, or cut-off voltage is simply the smallest value of voltage allowed in the discharging process. This voltage recognizes the state of the battery as "empty" and is the lower-end minimum voltage allowed for the battery to discharge. The value of cut-off voltage is chosen such that the properties of the battery aren't damage. Too low of a cut-off voltage will cause this damage while too high will cause the battery to halt operation while it still has useful capacity left to utilize. To increase the voltage of your battery, it is possible to arrange them in series. Parallel arrangement results in increased capacity. This is why when searching for a battery for this project, it is important to recognize if the characteristics of the cells in this regard. If a battery is mentioned as being a “2S” battery, then that means there are two cells connected in series. Likewise, a “2P” battery relates two the two cells being connected in parallel.

Capacity: The capacity of a battery defined as the current drawn by the battery times the amount of hours the current flows (Amp-hours). This is the most important figure to evaluate when selecting the proper battery for a project, and is a way to measure the stored energy in a battery. Capacity often is measured by the amount of current that the selected battery can deliver in one hour before it hits its lower end cut-off voltage. Selecting a battery with a higher capacity is associated with a longer runtime and battery life.

C-Rate: C-rates are an essential parameter to view when talking about a battery’s capacity, and allow the manufacturer to compare the desired value with the measured value. The C-rate compares the battery’s discharge rate to its capacity and is often listed in multiples such as 0.5C, 1C, 2C, 5C, etc. and specifies the speed at which a battery is charged or discharged. For example, if your capacity is 1000 mAh, a 0.5C rate equates to a discharge current of 500 mA, while a 2C rate equates to 2000 mA.For our project, it is essential to select the correct battery that satisfies these needs. The battery drives the system and supplies voltage to the components, so m figure of merits must be considered.

Types of Batteries: There are two main types of batteries: Primary and secondary. Primary batteries are non-rechargeable batteries that serve as a one-time use solution. These batteries excel at short discharges at low power levels. Examples of these batteries include alkaline, mercury, silver oxide, zinc air, and carbon-zinc batteries. Secondary batteries, on the other hand, are rechargeable and are utilized for long discharges at high power level applications. Examples of some secondary batteries include Lithium Ion, Lithium Polymer, Lead Acid, Nickel Metal Hydride, Nickel-Zinc, and much more. For this project, a rechargeable battery is needed. Therefore, it is necessary to compare and contrast different secondary battery types.

Nickel Cadmium or “NiCAD” batteries were once an extremely popular rechargeable battery choice amongst consumers. NiCAD batteries are realized using Nickel Hydroxide for the positive electrode, cadmium hydroxide for the negative, and potassium pydroxide serving as the electrolyte medium. Although they don’t last very long and only output put less voltage than non-rechargeable alkaline batteries, they have a very high energy density. They are also relatively inexpensive and are used widely in applications such as power tools, flashlights, and other cordless portable equipment.

NiCAD batteries, suffer from “memory effect”. Memory effect occurs if the battery is not fully discharged and greatly reduces the capacity of the battery if it is charged under these conditions. When charged correctly, NiCAD batteries can reach around 1000 charge/discharge cycles. It is important to select the correct charger when using a NiCAD battery, one that will not float or prevent the battery from fully discharging. While this is mostly perceived as a negative, this allows NiCAD batteries to tolerate full discharge periods for a long period of time without damage. Because of this, this battery is a good option if a durable, reliable solution is required.

NiCAD Batteries	
Pros	Cons
Low Cost	Memory Effect
Large number of Charge/Discharge Cycles	Loss of Popularity in Market
Durability	Discharges Quickly
	Environmental Concerns

Figure 53: NiCAD Batteries - Pros/Cons

Nickel Metal Hydride (NiMH) batteries have overcome NiCAD batteries in the market and many applications. NiMH batteries function using Nickel Hydroxide ad the positive electrode, a hydrogen-storage alloy as the negative, and potassium hydroxide as the electrolyte medium. They are about the same size as primary alkaline batteries yet provide more power. But unlike alkaline batteries, they provide a nominal voltage of 1.2V instead of 1.5V. NiMH batteries also carry some memory effect, but not as significant as NiCAD. They are also better for the environment and produce an even higher energy density. On the other hand, NiMH have a shorter work life and are not as durable when deeply discharged as the NiCAD batteries. NiMH batteries are rapidly taking over the NiCAD market and popularity, and have an increased energy density by about 1.4 fold. These batteries also have minimal internal resistance and are excellent for high current drain applications such as cameras, electric vehicles, and power tools.

NiMH Batteries	
Pros	Cons
Relatively Low Cost	Some Memory Effect
High Energy Density	Discharges Quickly
Low Internal Resistance	Self-Discharges in 2-3 Months
Easily Disposable	

Figure 54: NiMH Batteries - Pros/Cons

Lithium Ion Batteries: Lithium is a metal with extremely high electrochemical potential. While lithium is a very high energy density, is extremely reactive, and somewhat dangerous, the process of extracting the lithium ions from compounds instead of the chemical itself proves a way to increase safety measures. Lithium ion batteries are realized with carbon-coated copper at the positive electrode, aluminum-coated lithium compound at the negative electrode, and an electrolyte medium of a lithium salt.

There is almost zero memory effect in Li-Ion batteries, meaning that they can be recharged at any point within their discharge cycle without any repercussions. The energy density in lithium ion batteries succeeds NiCAD by about twice the amount and NiMH by about 60%, crowning them as one of the most compact rechargeable batteries in regards to energy storage. They also discharge at about only 6% per month, meainging that they can last up to 16.7 months without fully self-discharging. Being that they have a higher internal resistance, this means that they also do not charge as quickly as some of the secondary battery types.

Expense is also another thing to consider, Li-ion batteries cost a substantial amount more than NiCAD and NiMH batteries. This is partially due to protections implemented to avoid overcharging and excessive discharging, to reduce failure states and safety risks associated with Li-Ion batteries. If short circuited, Li-Ion batteries can cause a cell to smoke, catch fire, or even combust .They also require a more complex charging circuit, especially when adding more cells. Li-Ion batteries are of great use in applications where there is limited space but a large amount of energy is required. Seeing that, they come in different form factors such as cylindrical and prismatic shapes. They are easily fitted into devices such as laptops, cell phones, and portable electronics.

Lithium Ion Batteries	
Pros	Cons
No Memory Effect	High Cost
High Energy Density	High Internal Resistance
Low Self-Discharge Rate	Potential Safety Hazard
Easily Disposable	Require Protection Circuit
Variety of Shapes/Sizes	

Figure 55: Li-Ion Batteries - Pros/Cons

Lithium Polymer or “LiPo” batteries are very similar to Lithium Ion batteries in regards to energy density but use only a solid polymer electrolyte medium that resembles plastic film. This pouch for of lithium ion batteries suffer from decreased safety hazards of Li-Ion, being more resistant to overcharging and electrolyte leaking, while maintaining most of the positives. The dray polymer is cheaper to fabricate, making the LiPo a more cost effective option. This comes with a tradeoff however, in that the dry medium has poor conductivity, requiring most products implement gelled electrodes. LiPo batteries with gelled electrolyte function are almost the same as Li-Ion, in regards to charge time and the charging algorithm.

Lithium Ion Batteries	
Pros	Cons
No Memory Effect	High Cost w/ Protection Circuit
Slightly More Easier to Integrate than Li-Ion	Very High Internal Resistance
Easily Disposable	Potential Safety Hazard
Variety of Shapes/Sizes	Require Protection Circuit
Slightly Safer than Li-Ion	Lower Energy Density than Li-Ion
	Electrolyte only Conductive at High Temps

Figure 56: LiPo Batteries - Pros/Cons

Comparisons: for our project, it is important to weigh the options between these form factors by their pros/cons. Right off the bat, we can see that NiCAD is not an attractive option due to its “memory effect”. While it is a cost-effective solution, being able to charge during any point in time of the discharge cycle is an important feature in which “memory effect” removes. NiMH has positives associated with it: it is cost-effective and is safer to use than Li-Ion/LiPo, but its low nominal cell voltage would require multiple batteries to be connected in series. Depending on the supply voltage required, this can be an adequate solution to implement.

Li-Ion/LiPo dominates in regards to cell voltage and energy density. The non-cylindrical form factor options also allow for smaller and lighter products. Virtually no memory effect and the very slow self-discharge rate allow for ease of use charging for the user. For our project, Li-Ion/LiPo gains a slight edge over NiMH and drastic edge over NiCAD. The small size in weight will give us more room to add heftier components, such as the PCB into the limited housing space. For applications, Li-Ion/LiPo is the closer choice being used in many portable electronics whereas the other battery types are more commonly used in products that require greater durability and a deep discharge.

Type	Nominal Cell Voltage	Energy Density Wh/Kg	Cycle Life	Charge Time	Max Discharg e Rate	Cost
NiCAD	1.2V	Medium (40-60)	Long	14-16 hrs	High (>2C)	Medium
NiMH	1.2V	High (60-60)	Medium	2-4 hrs	Medium (0.2-0.5C)	Medium
Li-Ion/LiPo	3.3-3.7	Very High (>100)	Medium	3-4 hrs	Medium (<1C)	High

Figure 57: Comparison of NiCAD, NiMH, Li-Ion/LiPo Batteries

Battery Protection: Because of the potential hazard states associated with Li-Ion/LiPo batteries, protection circuitry is required to ensure that they are not overcharged or over discharged beyond their upper and lower voltage limits. Due to health and safety constraints for this project detailed previous in this report, this is a primary concern. Protection is provided in the form of over-current protection, over-temperature protection, over-voltage protection, and under-voltage protection.

Battery Considerations: for this project, selection of the specific battery heavily depends on the other power requirements of the components for this system, including: motors, microcontroller, and any other supply voltages for IC's on the final PCB. Because most ICs operate with a supply voltage minimum of $\pm$5V, consideration of 2S Li-Ion/LiPo batteries will be evaluated. Options lie in simply boosting the voltage of the battery using a switching regulator (discussed in section *Voltage Regulators* located later in this report). Either way, the supply voltage of the heavily considered TI Ultra-Low Power MSP430 microcontrollers lies within the wide range of 1.8-3.6V. Meaning; if a 3.7V nominal cell is used, it will need to be regulated within the correct range for the microcontroller.

The batteries to be compared will be Lithium Ion/Lithium Polymer batteries based on the findings above. Li-Ion/LiPo offers much more benefits for this project in particular, with its small form factor and high cell voltage. Most essential in regards to Lithium batteries is that there implemented safely, and a protection circuit is implemented. Many batteries have protection circuits built-in, but some do not.

RC (radio control) Lithium Ion/Lithium Polymer batteries offer little in these protection circuits. These batteries are used for radio controlled vehicles and applications that require a large amount of power and extremely high C-Ratings. RC LiPo batteries will fully deplete the raw cell before risking damage to an RC vehicle. This means that these batteries are suspect to damage, and safety concerns. Because of this, these batteries are the less expensive option and do not offer much for this project based on health and safety constraints unless our own protection circuitry is implemented.

Other types of batteries have this protection circuit implemented. Whether it is hard-cased Lithium-Ion batteries found in cellphones, or LiPo batteries sold for do-it-yourself projects, many of these batteries are safer for applications in which a user is in close proximity to the device. Cell phone batteries offer the protection circuit within the hard-shell casing. While LiPo batteries usually have a protection circuit soldered above and it is marked with colored tape.

LP785060: The LP785060 is a Lithium Ion Polymer Battery sold by Adafruit offers a relatively high capacity at a decent price. This battery has a JST-PH connector already attached which makes it easy to implement with a charging circuit. The adafruit website recommends charging this battery at 0.5C (1200mA) or less using Li-Ion/LiPo CV/CC charging methods.

EQ40 LiPo Battery: The EQ40 LiPo battery pack is a cell phone battery that is included in the Motoralo XT1254 Droid Turbo. This battery has a very high capacity of 3900 mAh and nominal voltage of 3.7 V. This the connector of this lipo pack is a small breakout PCB with the positive and negative terminals surrounded by plastic casing. The cost of this battery can range from $10-$40 based on the place of purchase.

Samsung Galaxy Note 4 Li-Ion Battery: The Samsung Galaxy Note 4 Li-Ion Battery offers a high capacity in a small, thin, form factor. The capacity measures about 3220 mAh with a nominal voltage of 3.7V. These batteries can be found for around $13 and offer a good solution if enough length is provided in the housing.

3.3.4.3 Voltage Regulators

Many different components of our system will require different voltage levels. DC voltage regulators serve as an option to increase (boost), decrease (buck), and invert (buck/boost) voltage levels. Sending the correct supply voltage to the components is important as to not damage them or cause malfunction. Voltage regulators come in two types: Linear and switching. Both have different uses and their own advantages/disadvantages which is essential to be covered in regards to our project.

Linear Voltage Regulators: Linear voltage regulators are the simpler of the two and operate by sending a voltage to the output via a current source. Linear regulators are only used to "buck" or step-down voltage levels, requiring that the input voltage must be larger than the output voltage. Linear regulators come in 2 basic variations: Standard and Low-Dropout (LDO) regulators.

Standard linear regulators operate by using a pass device. In the case of a standard NPN regulator, the pass device contains by a PNP transistor and NPN Darlington pair as seen above. Through feedback, the output voltage is controlled and sensed via a voltage divider with two resistors. A reference voltage V_{REF} is applied to the negative terminal of the error amplifier which manipulates and adjusts the output voltage to ensure that the input voltages are equal. This causes the feedback to hold the output voltage at a certain (regulated) value.

There is a voltage which causes the circuit to stop regulating; however, this is called dropout voltage. Dropout voltage is the differential voltage at which the input voltage reaches near the value of the output voltage, stopping the regulatory properties of the circuit. For a standard regulator, the dropout voltage usually lies within the range of 1.5-2V. This means that if you desire to regulate a 6V input to a 5V output, for example, you must use a low-dropout (LDO) regulator.

LDO Regulators: Low Dropout (LDO) regulators are designed have minimum dropout voltage such for use for applications that require the input to be very close to the output. Comparing with the previous circuit, the schematic above shows that the NPN Darlington pair is replaced with a PNP transistor. If using a FET regulator, most LDO linear regulators are realized with a P-Channel/N-

Channel FET. Operating in the linear region, the pass element drops input voltage to the level of the desired output and the error amplifier will drive the gate of the pass element such that the correct output voltage is achieved. Because of this, LDO regulators can be used to remove ripples to components that are sensitive to input supply voltage noise. LDO's can quantify the amount of ripple reduced by Power Supply Rejection Ration (PSRR), also known as Power Supply Ripple Rejection Ratio. PSRR is defined as follows:

$$PSRR(dB) = 20Log_{10}(\frac{A_V}{A_{VO}})$$

Where A_V represents the power supply gain of the regulator feedback loop and A_{VO} represents the open-loop transfer function of the input to the output nodes (V_{in} toV_{out}). PSRR is a specification to look for when selecting an LDO regulator, as it is the quality of the regulator's ability to reject noise. Efficiency is another important parameter to search for, and can be calculated as follows:

$$Efficiency = \frac{I_o V_o}{V_i(I_o + I_q)} * 100\%$$

Efficiencies of linear regulators overall remains their biggest downfall. While they are cheap, their efficiency does not compare with switching regulators, which can hold above 85%. One key characteristic of linear regulators to consider, however, is that their efficiency increases the smaller the difference between the input and output voltages (dropout voltage) is. This makes LDO linear regulators inherently more efficient than standard linear regulators. For battery powered applications, and in our project, this makes the use of an LDO regulator an attractive option. For AC applications, it is fine to use a standard linear regulator as it is lower and cost and provides more load current, and the dropout voltage is usually high.

Key details of linear regulators:

Linear Regulators	
Pros	Cons
High Ripple Rejection	Can only "Buck" Voltage
Low Cost	Low Efficiency
Less Complex	High Waste Heat
Easy to Integrate	

Figure 58: Linear Regulators - Pros/Cons

Switching Regulators: Switching voltage regulators uses a switching element to convert the input into AC, then transforms it into a differential voltage using elements such as inductors and capacitors and converts it back to a DC voltage. Switching regulators are more complex than linear regulators, and are somewhat more difficult to implement properly. Because of the rate of the switching, they also produce more substantial ripple than linear regulators. On the other hand, the waste heat is minimal and efficiency outperforms linear regulators by a substantial amount. Switching regulators come in many different topologies, and are commonly known as “converters”. The most popular of these types are buck, boost, buck/boost, and flyback regulators.

Buck converters/regulators are simply a switching regulator used to produce a DC voltage that is lower than the output. These serve the same function as linear regulators, but operate under a different process, using the law of inductance and the fact that current cannot change instantaneously. They operate using a switch (usually a MOSFET) controlled by pulse width modulation that determines the ON/OFF cycles and the flow of current.

Boost converters serve as the opposite of buck converters, and produce a DC voltage that is higher than that of the output. The difference lies in the placement of the inductor, switch, and diode. In this case, the current is increased across the inductor when the switch is closed or in its ON state. When the switch opens, the current decreases in the inductor, requiring that the switch end of inductor to forward-bias the diode: Charging the capacitor to a higher voltage level than the input. These regulators can be used for application where you need to step up your battery voltage to meet a certain supply voltage for a component such as a 3.7V Li-Ion battery being stepped up to a 5V supply requirement.

Buck-Boost converters switch the polarity of the input voltage to produce an inverted output voltage by combining principles of buck and boost converter topologies. For battery applications buck-boost is useful when you need to buck the voltage at a certain battery level, and boost the voltage when discharging of the battery causes the level to drop. It is also used as a DC inverter such that negative supply voltages can be applied to components.

Flyback converters operate as buck-boost converters but have the ability to create multiple output voltages, negative or positive in polarity. Flyback regulators are popular in battery-powered systems and low-powered designs due to the implementation of the transformer, which makes it less suitable for high power applications. This transformer also provides galvanic isolation to ensure that high voltage is isolated from other components.

Key details of switching regulators:

Switching Regulators	
Pros	Cons
High Efficiency	Higher Cost
Can Buck, Boost, Invert Input Voltage	Difficult to Implement
Low Waste Heat	Higher Ripple

Figure 59: Switching Regulators - Pros/Cons

Regulator Considerations: For this project, the voltage will be stepped down to the 1.8-3.6 voltage of the Ultra-Low-Power MSP430 FR59xx series. Depending on the type of battery used – 2S or 1S, the input voltage of the regulator will be chosen accordingly. A Boost switching regulator will also need to be considered to boost the voltage to motors and possible control board. Choice of regulators depends heavily on other components within this project, which is why many different components and options will be evaluated.

LM5175 Wide VIN 4-Switch Synchronous Buck-Boost Controller: The LM5175 by Texas Instruments is DC/DC controller that allows for buck and boost regulation of the output. This controller allows a wide range input voltage ranging from 3.5 to 42 V as well as a flexible output voltage of 0.8 to 55V all while being able to supply enough current to each motor for this project.

TPS70630 Linear Regulator: The TPS70630 by Texas Instruments allows for an input voltage range of 2.7 V to 6.5 V and has a minimal dropout voltage of 245 mV at 50 mA. This regulator will allow dropping from a 5V supply rail to the MSP430 ultra low power microcontroller used in this project.

3.3.4.2 Charging

In order to charge the Li-Ion/LiPO battery for this project, several charging methods must be investigated. Li-Ion and LiPO batteries have almost identical charging techniques. Most chargers employ energy restoration to the Lithium battery using a constant current-constant voltage method in the following four stages consecutively: Trickle charge, constant current charging, constant voltage, and charge termination.

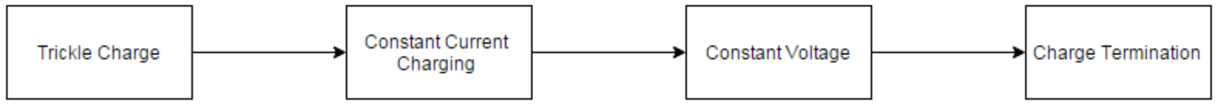


Figure 60: Lithium Charging States (CC-CV)

The trickle charge is first applied to the cell when the voltage is below the trickle charge threshold (around 3V), supplying a constant charge of about 10% of the capacity. When the voltage of the cell rises above this threshold, the charge current is increased from 0.1 C to the value of 0.2C-1C, charging the cell to its full voltage. When the full voltage of a Li-ion cell is reached, 4.2V, the next stage constant voltage, is employed where the constant current changing is halted. After this, the charge termination stage takes effect such that no trickle charge is applied, ceasing any probability of damage to the battery. For Lithium batteries, the common charging methods are Linear, Switch-Mode, and Pulse charging. Coupled with advantages and disadvantages, each of these charging techniques must be evaluated.

Linear Charging: Linear charging is good to use when "ease of use" is of high consideration. However, due to the power dissipation issues associated with them, they lack efficiency. Linear chargers are relatively used with a regulated input, and due to the simplistic nature of them, they are usually cheaper.

Pulse Charging: Pulse charging acts as an intermediary between linear and switch-mode chargers. Operating by sending pulses of input current to charge the batter, this pulsing method increases the efficiency compared to that of a linear charger. Negatives of this, however, is that there needs to be a current limit on the source voltage of the charger.

Switch-Mode Charging: Switch-mode charging offers a wide range of input voltage, and can handle more unregulated inputs. Due to the efficiency of switch mode charging, it is a great selection to minimize power dissipation. The downfall of switch-mode chargers, however, is that they are more complicated to integrate and require more space on the PCB.

Charging Definition Terms: When searching for a charger there are common terms to be defined. These terms are listed below.

Name	Definition
OVP	Overvoltage protection
DPPM	Dynamic Power-Path Management
TD	Termination Disable Input
ITERM	Termination Current Programming Input
SYSOFF	System Enable Input
PG	Power Good for AC Adapter and USB
CHG	Charge Status Indicator Output

bq24xxx Series Battery Charger: The bq24xxx series from Texas Instruments offer different options of Lithium-Ion cell battery charging. Below is the comparison of different of the different bq24xxx battery charges.

Specification or Feature	bq24230	bq24232	bq24072	bq24075	bq24075T
Minimum Vin (V)	4.35	4.35	4.35	4.35	4.35
Maximum Vin (V)	6.4	10.2	6.4	6.4	6.4
VOUT(REG) (V)	4.4	4.4	V_{BAT} +225mV	5.5	5.5
VOVP(V)	6.6	10.5	6.6	6.6	6.6
Battery Charge Voltage (V)	4.2	42	4.2	4.2	4.1
VDPPM (V)	VO(REG) – 100mV	VO(REG) – 100mV	VO(REG) – 100mV	4.3V	4.3V
Functions	TD	ITERM	TD	SYSOFF	SYSOFF
Status Indication	CHG, PG	CHG, PG	CHG, PG	CHG, PG	CHG, PG
Adapter Current Limiting	Yes	Yes	Yes	Yes	Yes
Max Input Current (A)	0.5	0.5	1.5	1.5	1.5
Max Charge Current	0.5	0.5	1.500	1500	1500
Package	3x3QFN-16	3x3QFN-16	3x3QFN-16	3x3QFN-16	3x3 QFN-16
Temp Sensing Mode (TS)	Current Mode	Current Mode	Current Mode	Current Mode	Voltage Mode
USB	Yes	Yes	Yes	Yes	Yes
Termination Current	Internally Set	Programmable	Internally Set	Internally Set	Internally Set

Figure 61: bq24xxx Series Battery Charger Specifications

bq2423x Lithium-Ion Battery Charger: The bq2423x Lithium-Ion Battery Charger is a battery charger IC from Texas Instruments that offers USB charging for the system and is geared toward Low-Power applications. Bq2423x charger comes in two different device configurations: the bq24230 and bq24232 which differ in the Overvoltage protection of 6.6 V and 10.5 V, respectively. The regulated voltage output of the IC is 4.4 V. A Major feature of this chip is the Dynamic Power-Path Management (DPPM) which can use the source of the input to power the battery as well as the system. The system is powered by the battery when the input source is removed (in this case the USB connection). This allows the system to run with no battery pack, which is ideal for testing purposes. Due to the better overvoltage protection and other key specifications, the bq24230 will be considered.

Pin Name	Input/Output	Function
TS(1)	Input	Monitors 10k external NTC thermistor. If TS is not utilized, connect 10k from TS to VSS to maintain valid voltage level on TS.
BAT(2,3)	Input/Output	Charger Power Stage Output and Battery Voltage Sense Input. Connect this pin to POS terminal of battery. Bypass Bat to VSS with 4.7-47uF ceramic capacitor.
$\overline{\mathrm{CE}}$(4)	Input	Charge Enable Active-Low Input. To disable battery charging, connect CE to high logic level. Inversely, connect CE to low logic level to enable battery charge.
EN1/ EN2(5/6)	Input	EN2=0, EN1=0: 100 mA USB100 EN2=0, EN1=1: 500 mA USB500 EN2=1,EN1=0: Ext Res ILM to VSS EN2=1, EN1=1: Standby Mode
PGOOD(7)	Output	Open-Drain Power Good Status Identification Output
VSS (8)	-	Ground
CHG (9)	Output	Pulls to VSS when battery is charging
OUT(10,11)	Output	Provides regulated output when input is < OVP and > than regulation voltage
ILM(12)	Input	Adjustable current programming input
IN(13)	Input	Input Power connection
TMR(14)	Input	Timer programming input
TD(15)	Input	Termination Disable Input
ISET(16)	Input/Output	Fast-Charge Programming Input

Figure 62: bq2430 Pin Specifications.

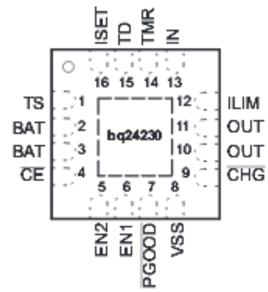


Figure 63: bq24230 RGT Package (*Pending Texas Instruments)

Using the bq24230 charger coupled with the Buck/Boost converter (TPS63030) a complete charging process can be realized. This process takes input from the source (USB) and charges the battery all while supplying voltage to the system and MCU. As 3V is also within range of our supply voltage, a low dropout regulator can be substituted for the Buck-Boost converter to simplify the integration and save board space.

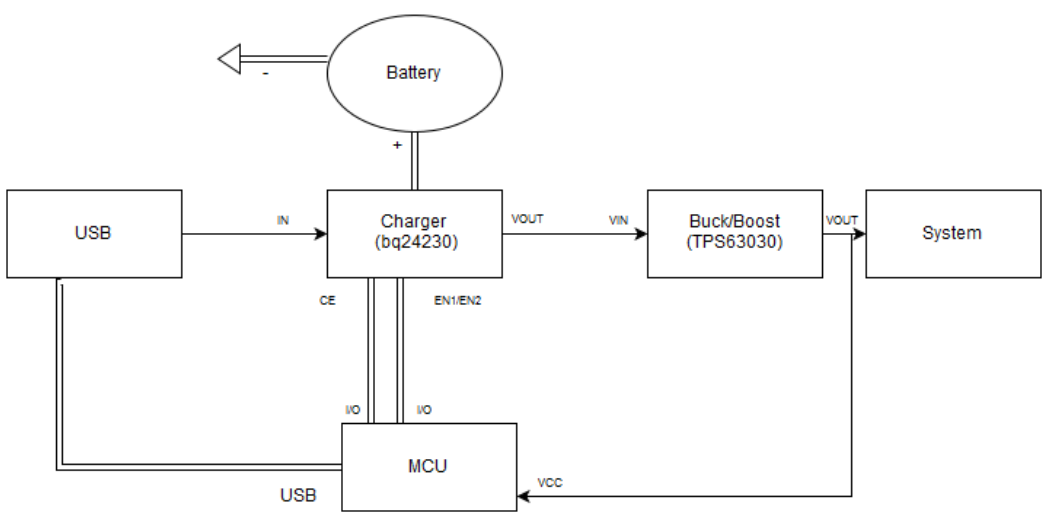


Figure 64: ba24230 Charging Process.

bq24103 series Switched-Mode Li-Ion/LiPo Charge Management IC: The bq2412x by Texas Instruments is a charge management device that is designed for many portable applications. Features of this IC include PWM controller, power FETs, high-accuracy current/voltage regulation, charge preconditioning, status of charge, and charge termination. Benefits of using this device is that it offers compatibility with 2S batteries through a pullup resistor from the CELLS pin to VCC.

MCP73831 Charge Management Controller: The MCP73831 is another consideration for Li-Ion/LiPO charging in this project. This controller features an output for battery charge status indication. Located in the in the Adafruit Trinket Pro Backpack, implementation of this charger on the Backpack makes it easier for prototyping and implementation. The 5V output of the backpack must be stepped down for the 1/8-3.3V Supply range of the MSP430 microcontroller.

Fuel Tank BoosterPack: The fuel tank BoosterPack offered by Texas Instruments and element14 allows the rechargeable Lithium Ion and/or Lithium Polymer battery in this project to be powered and can be used for easy prototyping. The fuel tank booster pack is compatible with all Texas Instruments Launchpads, including the MSP430FR5969 that we will be using. Features of this booster pack board include:

- BQ24210 Li-Ion Battery Charge
- BQ27510-G2 Gas Gauge
- LED (Low-Battery Indicator)
- LED (Charge Indicator)
- USB (Micro)
- Attachable 3.7 1200mAH LiPo Battery
- Outputs:
    - Voltage
    - Current (Average)
    - Capacity
    - Temperature of Battery
    - Charge State

The **BQ24210 Li-Ion Battery Charger** is used for several space-limited applications such as smart phones and electronic handheld devices. This IC requires that the power source at the “VBUS” pin is greater than the lockout threshold of 3.3 volts and less than the upper threshold of 7.5 volts. VBUS is the input for the charging source. This input is received from the USB port charge connector. The BAT pin is the connection of the battery, which provides current to the batter/system. While the CHG pin is responsible for the charge monitoring and LED states. This Li-Ion charger has four different operations: Sleep, charge, load, and suspend mode. Charge mode charges the battery to full capacity using a first stage which reconditions the battery using discharge and then consecutive constant current, constant voltage stages. The load operation powers the load at VBUS, while the sleep mode reduces the standby current. Suspend mode turns off both of the internal transistors inside the IC, stopping any charging operations.

The **BQ27510-G2 Gas Gauge** is an IC peripheral integrated in the Fuel Tank BoosterPack which offers fuel gauging for Li-Ion battery packs. Fuel gauges determine the charge and energy remaining in this case, the Lithium Ion battery, and estimate the consequent time remaining at which the battery can hold its capacity. The bq27510-G2 provides such information as state-of-charge (SoC), time-to-empty, and time to full. State of Charge is an important parameter for evaluating battery performance, and can accurately prevent overcharge or unwanted discharge. Simply an expression that of the battery's capacity, state of charge can be used to see how the capacity in the battery changes with respect to time. Time-to Empty and Time-to full are just as they are titled: the time necessary to fully discharge and charge the battery.

Using a series of small resistors from the range of 5m-20m, the voltage is measured by the fuel gauge. Cell impedance is also found based on the current, open-circuit voltage, and loading cell voltage. This IC offers five different power modes: NORMAL, HIBERNATE, SLEEP, SNOOZE, and BAT INSERT CHECK mode. Normal mode functions to take the average current, voltage, and temperature measurements. The most power is consumed in this mode, so and it is the default mode operated when no other modes are activated, and can be excited by simply activating another power mode. Hibernate mode is useful when low power is needed, and the system the gauge is acting on is in its own hibernation state. Sleep mode is activated when the average current falls below the sleep current, which is programmable and can be set manually. The gauge exits sleep mode when if the average current rises above the sleep current. Snooze mode is comparable to sleep mode in that it activates when the average current is below the sleep current, but differs in that it exits when any communication activity is detected with the fuel gauge.

Commands (indicated by *Command()*) are used to extract/implant information within the registers and flash data locations of the chip. Information regarding the battery cell is stored in the in flash memory within the device which can be accessed via commands, fuel gauge evaluation software, or data flash access commands .These registers are defined as either "control" or "status" registers. Using I2C from the system's microcontroller, the commands can be sent to the bq27510-G2 for execution. The standard commands are 2-bytes each and allow the battery information to be written and retrieved. The command codes of each function are used to determine whether to read/write the function and initiation of the command function. Some of these standard commands include capacity measurements: such as FullAvailableCapacity(), RemainingCapacity(), NominalAvailableCapacity(), as well as other important measurements such as Voltage(), and Temperature ().

3.3.6 Display

Displays will be considered for this project in order to change between the different grips/gestures. Other features could be implemented such as battery life. In the process of researching displays we made sure they were all compatible with the MSP430 and were “BoosterPacks”. A BoosterPack is a plug-in module that fits on top of the LaunchPad. The BoosterPack plugs into a consistent and standardized connector on the LaunchPad and allows for developers to explore different applications enabled by the TI microcontroller. In doing this there is an assurance that the display and microcontroller will work together properly.

3.3.6.1 Electronic Paper Display

An EPD, or Electronic Paper Display is a low power solution for many applications that require a frequently static display. These displays are known as bistable displays, which correlates to the system having two different equilibrium states. This means that no power is drawn when the display is either of its equilibrium states. Because of this, EPDs are capable of near zero current draw when the image on the display remains static.

Many different technologies are created to realize these displays. Electrophoretic is one of these technologies, where an e-ink layer is between a top and segmented bottom electrode. The top electrode is transparent and is usually made of glass or plastic. The ink contained in the center is created from positive and negatively charged white and black particles, respectively. Voltage is applied to the bottom electrode which either repels or attracts the black/white particles based on the polarity. This in turn, causes one of the pigmented particles to accumulate under the transparent top layer, creating a pixel. Because of the high reflectivity when the white pigmented particles are surfaced around the top layer, Electrophoretic displays do not require a backlight like LCDs and are easily readable in the sunlight.

EPDs have also been made flexible which sought out for in certain applications. Due to its flexibility and very low power consumption EPDs are ideal for this project. With the flexibility trait we can keep the natural look of the arm while still embedding the display into the arm. These types of displays are ideal for electronic shelf labelling and other applications where screen content does not change frequently.

Electronic Paper Display (EPD)	
Pros	Cons
Flexible – The display itself can be flexed to a very liberal degree	Less Attractive – They are less attractive to technologies like LCD, LED
Low Energy – This type of display only uses power when changing the image	Reading with dim light – No backlight means that reading in the darkness and in little light is made difficult
Viewing Angle – Wide viewing angle	Low Refresh Rate – With the refresh being so low fast moving menu, pointers, and scrolling options are not well implemented
Readability – More readable in sunlight	Color – Lack of color
Size – Small, thin footprint	

Figure 65: Electronic Paper Display - Pros/Cons

Texas Instruments Electronic Paper Display Booster Pack: This booster pack comes with varying sizes for the ePaper display (1.44", 2", and 2.7"). Ideally for this project to save space we would choose the 1.44". There are 20 pins at the rear side to stack on Texas Instrument's LaunchPad board and also 20 control pins with the product or development board to drive EPD via SPI interface. Price of this BoosterPack is $24(USD) and it uses 20 pins of the MCU. To use this Booster Pack with the MSP430FR5969 LaunchPad some of the jumpers need to be adjusted. Next the flexible circuit of the electronic paper display is connected to the FPC connector of the electronic paper display extension board. This BoosterPack supports Code Composer Studio™ and Energia IDE. After testing, the electronic paper display itself without the extension board and the MCU without the Launchpad will be placed on the PCB.

Pin Number	Description
1	VCC 10-3.3V
2	LED1
3	UART_RX
4	UART_TX
5	SW2
6	TEMPERATURE
7	SPI_CLK
8	BUSY
9	PWM
10	/RESET
11	PANEL_ON
12	DISCHARGE
13	BORDER_CONTROL
14	SPI_MISO
15	SPI_MOSI
16	RST/SBWTDIO
17	TEST/SBWTCK
18	FLASH_CS
19	/EPD_CS
20	GND

Figure 66: Texas Instruments EPD BoosterPack Specifications

BCD (Bi-stable Cholesteric) - These types of display do not require any power to drive the display. Power is only used when the image is refreshed. These displays are especially good with not needing backlight and retaining viewing angles. Since there is no backlight, these displays are thinner and lighter making them ideal for our application.

Bi-Color display BoosterPack- This display is made from a 128 x 64 dot matrix which allows for a wide viewing angle. The BoosterPack has a 4-wire SPI interface and requires 2.8 V. Price of this BoosterPack is $35.16 and uses 8 pins.

Pin Number	Symbol	Description
1	VCC	Power supply voltage(3.3V)
2-5	NC	No connection
6	RS	Data/Register select, set high for data input and low for register input
7	CS	Chip Select, low active
8-13	NC	No connection
14	RESET	Reset signal input, low active
15	SCLK	Serial clock input
16-17	NC	No connection
18	SDA	Serial data input
19	BUSY	Chip busy signal output, output high level indicates busy status
20	GND	Ground

Figure 67: Bi-Color Display BoosterPack Specifications

3.3.6.2 LCD Display

LCD's (Liquid Crystal Display) block light rather than emit light making them more energy efficient than LED (Light-emitting diode) and plasma displays. Its low power consumption allows it to be used with battery powered electronics. LCDs have a sharp, clear image, and are used in many electronic applications. Implementation of an LCD is a consideration for this project.

Liquid Crystal Display (LCD)	
Pros	Cons
Sharpness – Image is perfectly sharp at the native resolution	Resolution – Fixed pixel resolution format determined at the time of manufacture that can't be changed
Geometric Distortion – No geometric distortion at the native resolution	Interference – Depending on the board you may not be able to entirely eliminate the digital noise
Brightness – Produces very bright images	Viewing Angle – The viewing angle is limited, needs to be viewed as straight as possible
Screen Shape – Space saving form factors	Black-Level, Contrast, and Color – Difficulty producing black and very dark grayscale images
Physical – Small, thin footprint	White Saturation – The LCD intensity is prone to saturation and compression
	Color and Gray-Scale Accuracy – The internal Gamma and the greyscale of an LCD is irregular, prone to dithering
	Bad Pixels and Screen Uniformity – The panel may not be uniformly illuminated by the backlight which results in uneven shading over the screen
	Motion Artifacts – Moving or rapidly changing images causes severe motion artifacts
	Aspect Ration – The common aspect ratio of 5:4 is noticeably smaller than the 4:3 for almost all other displays
	Cost – More expensive than most displays

Figure 68: LCD Display - Pros/Cons

Kentec QVGA Display BoosterPack: This booster pack adds a touch screen color display using the 320 x 240 pixel SPI controlled TFT QVGA display. Price of this BoosterPack is $24.99(USD) and the display uses 14 pins from the MCU. This BoosterPack supports Code Composer Studio™ and Energia IDE.

Features
Kentec TFT LCD -3.5 inch QVGA(32x240 resolution) -SPI interface -4-wire resistive touch screen -White LED Backlight
LED backlight driver circuit
Compile with BoosterPack standard for use with 20 and 40 pin LaunchPads

Pin Number	Description
1	3V3
2-6	NC
7	LCD SCL
8	LCD SDC
9-10	NC
11	R18 or TOUCH YN
12	NC
13	LCD SCS
14	NC
15	LCD SDI
20	AGND
21	5V0
22	GND
23	R16 or TOUCH YP
24	R15 or TOUCH XP
25-30	NC
31	R17 or TOUCH XN
32	LCD RST
33-39	NC
40	LED PWM

Figure 69: Kentect QVGA Display BoosterPack - Pros/Cons

3.3.6.3 Comparisons

In the process of researching displays we made sure they were all compatible with the MSP430 and were “BoosterPacks”. A BoosterPack is a plug-in module that fits on top of the LaunchPad. The BoosterPack plugs into a consistent and standardized connector on the LaunchPad and allows for developers to explore different applications enabled by the TI microcontroller. In doing this there is an assurance that the display and microcontroller will work together properly.

When selecting from the aforementioned displays many variables need to be accounted for. First is implementation of the display. Are there resources on the web to be able to decipher how to communicate to the display? Being able to communicate with the board is important. Initially, figuring out how to display characters/images to the screen display is needed. This is done in parallel with using the microcontroller. The more resources on the web for a particular display the better chance of not running into obstacles/miscommunication between the devices used. All three of the displays mentioned above have at least the minimal information of what each pin is used for. Next, cost of the display. With such a project that has many different portions going into it there comes a budget. The displays are roughly around the same price range with the Bi-color display being the most expensive. Next, the amount of pins being used up from the microcontroller. The lower the amount of pins used by the display the more pins we have available to implement other portions of the project.

	Kentec QVGA Display	Bi-color display	TI EPD
Cost	$24.99	$35.16	$24
Number of Pins Used	14	8	20
Resource Available for Assembly	Most	Least	In between
Best Feature	Touch Screen	Viewing Angle	Flexible

Figure 70: Display Comparisons

From the analysis the Kentec QVGA Display was chosen. The reason the Kentec GVGA was chosen is because the touch screen feature tends more towards what the display should do for our project. The display will be embedded into a crevice in the arm and provide the user the option to switch from gesture to gesture. With the addition of the touch screen there is no need for extra buttons or a switch to be able to switch the gestures. Also, the Kentec QVGA display does not only have the greater amount of resources available on the web but also better quality of resources coming straight from the Texas Instrument website.

4 Project Design

For this project, the primary plan is to have three gripping actuation methods. The first design will incorporate the use of a button to cycle through the different gestures. The automation of the gestures will be performed by 4 internal motors. The “pinky” and “ring” are usually connected within all but a select few gestures. For this reason, there will be a single motor controlling the last two digits of the hand. The middle and pointer finger are offered their own subsequent motors. For notation purposes in this report, the motors will be denoted as follows:

- Motor 1: Pinky/Ring Finger
- Motor 2: Middle Finger
- Motor 3: Index Finger
- Motor 4: Thumb

The thumb is also having its respective motor and is planned to be placed on a swivel to select one of two positions. The “first” position, known as THUMB-OUT, is where your hand remains flat and “in-line” with the rest of your fingers, with the top of the capsule lining almost parallel with the rest of the finger knuckles.

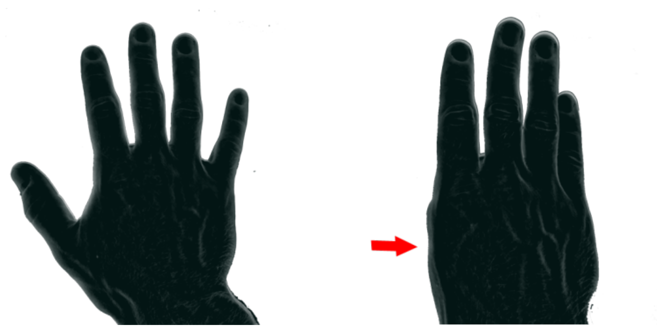


Figure 71: THUMB-OUT vs. THUMB-IN Position

The second position, known as THUMB-IN, dictates thumb capsule perpendicular to the knuckles, allowing for a whole different variety of grips. The position of the thumb may be measured via a position sensor to tell the other fingers if a certain gesture is possible. The position change of the thumb will be altered via a separate button/switch or manually moved by the user.

Close-In Grip is the most basic of all the gestures in this project. This grip is the standard when dealing with most 1-grip bionic arms on the market. It is used for strong grasping and grabbing of times with as much force as possible, as well as a secure, firm handshake. The standard Limbitless bionic arm functions with this grip.

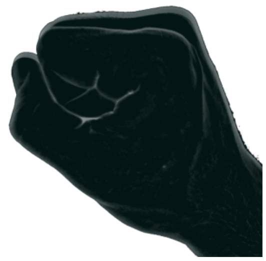


Figure 72: Close (In) Grip

Close-Out Grip is simply a variation of the Close-In grip. This grip the thumb is moved to the "THUMB-OUT" position. This allows the user to "hook" or grab items that were once unmanageable with the thumb in the way. This is useful for grasping light objects with handles.

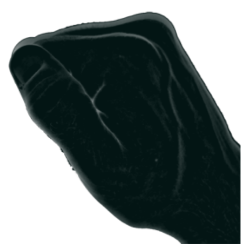


Figure 73: Close (Out) Grip

One-Finger Pinch Grip is a gesture that offers added precision in picking up small items for the user. This grip operates by keeping all fingers idle with exception do the pointer finger and thumb. The thumb must be placed in the "THUMB-IN" position and the pointer finger is then actuated to close. This grip is considered for use due to adding functional precision and picking up small items in locations where space is limited.

Figure 74: One-Finger Pinch Grip

Two-Finger Pinch Grip: The Two-Finger Pinch is identical to the One-Finger pinch grip with the middle (second) finger actuated with index. This grip allows for wider objects to be grasped with greater balance and stability. The thumb is also remained in the THUMB-IN position for this grip.

Figure 75: Two-Finger Pinch Grip

Point Grip is ideal for pressing buttons, switches, or any application that requires an active index finger. Every digit is closed besides the index and the thumb is in the THUMB-IN position.

Figure 76: Point Grip

These gestures will be implemented and actuated via the use of four motors total. Wires tied to the servo horn will pull the fingers down. Switching between these grips will be performed by the use of a button or capacitive touch screen. Upon switch of the grip itself each “Pre-Grip” state will be performed. For example, If the “One-Finger” pinch grip is to be performed, the Motors 1 and 2 must be closed while Motor 3 remains open. A battery LED indicator will be used to check the internal state of the battery, as well as a functional switch that operates the ON/OFF state of the device itself. The servo motors themselves will be cased inside the hand to save space. The electronics will be surrounded by a 3D-printed housing unit called the electronic housing (ECH).

Input to actuate these various grips will be performed via electromyography (EMG) sensing. Connected to the EMG sensor system will be an auxiliary port allowing for plug-in electrode leads. The potential difference leads will be placed in-line on the user’s bicep, and the ground lead on the elbow. When the user flexes, actuation of the motors will perform the selected grip function. Calibration methods will be coded into the FRAM to account for the user’s specific voltage level upon flexion of the arm muscle. This is to provide different users the ability to use the arm without altering the values manually. A button to start this calibration process will be implemented and available to the user.

4.1 Hardware

This section denotes the description of the electronic hardware. The major electronic hardware in this project consists of: EMG Sensor System, Microcontroller, Motors, and the Battery/Power Supply. The EMG sensor system sends the voltage signal to the MSP430FR5969 Microcontroller for analog-to-digital conversion. Both of these hardware components will be housed in a unit called the “Electronic Housing” (ECH). The motors will be located outside of the ECH, closer to the hand and will be controlled by the MSP430FR5969 via PWM (Pulse Width Modulation). The battery and power supply system is connected to the EMG Sensor, microcontroller, and motors to provide sufficient supply voltage and current necessary to run the components.

4.1.1 Hardware Block Diagram

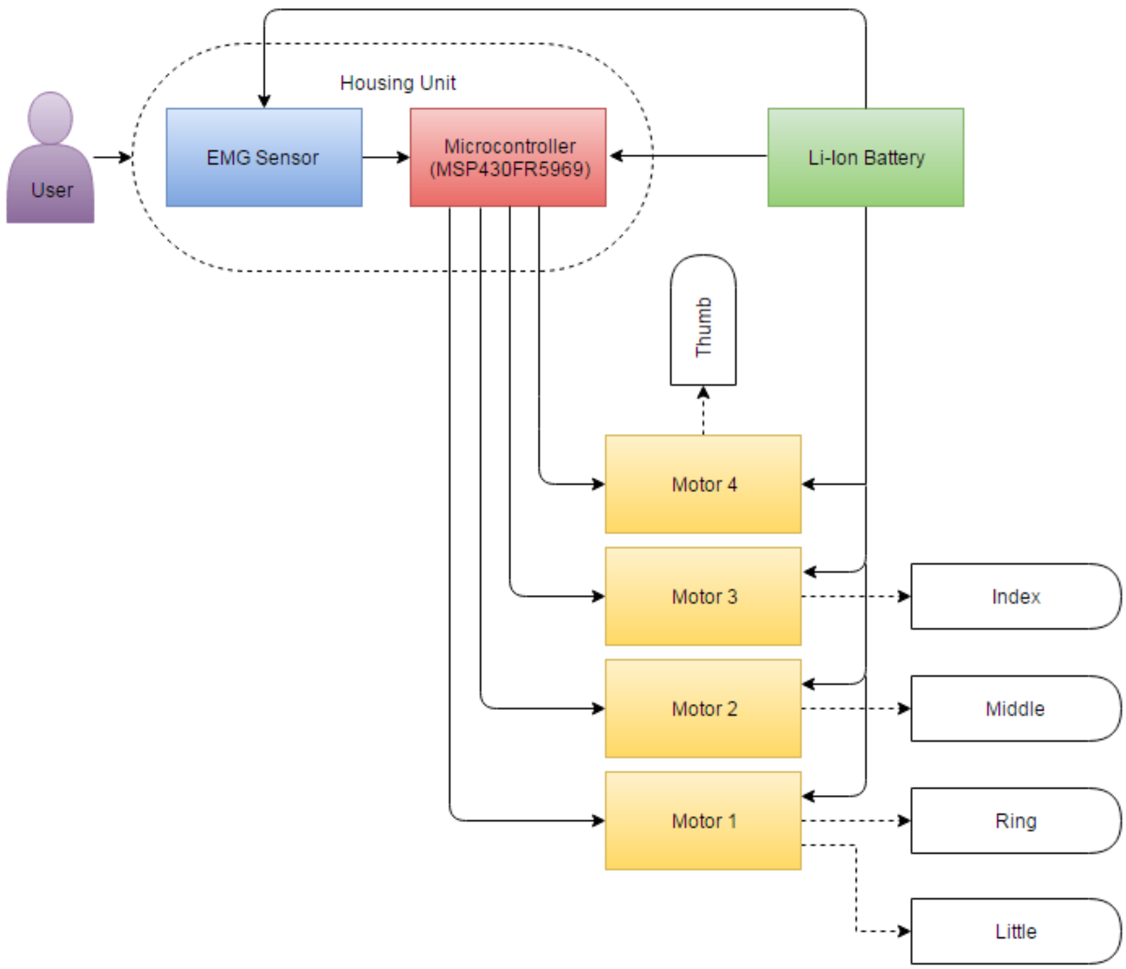


Figure 77: Hardware Block Diagram

4.1.2 Implementation

Implementation of all sub systems will be described in this section. Each member of the group is responsible for implementing a major specific component of this project. The division of the implementation is as follows: Microcontroller Implementation, Motor Implementation, EMG Sensor Implementation, and Power Supply Implementation.

4.1.2.1 Microcontroller/System Implementation

Implementation of the microcontroller serves as the central of the system. The microcontroller receives the full-wave rectified, smoothed EMG signal that will serve as the control signal to output for the motors. The MSP430FR5969 will be used for this project. The DCO generates the CPU clock and master clock. The Watchdog Timer is capable of operating as simple timer, and the GPIO pins and all peripherals have extensive interrupt capability. The general implementation of the real time clock (RTC) is not difficult. It has a timer/counter giving interrupts and a CPU routine to count these interrupts. This clock uses the LFXT1 oscillator in LF mode with a crystal. Timer A module is capable of slope A/D conversion, PWM output, and UART operation. Pulse width modulation (PWM) is used to control the rotation of the servo motors. The pins to use for PWM will have timer A or timer B capability. The four modes of operation for the timer are listed in the table below. The times are helpful when deciding how to implement the PWM. Only way to pass this by is if multiple motors are going to be using the same frequency.

Stop	The timer is stopped
Up	The timer counts from zero to the value of TACCR0
Continuous	The timer counts form zero to 0FFFFh
Up/Down	The timer repeatedly counts from zero up to the value of TACCRO (+1) and then back down to zero

Figure 78: PWM Timer - Modes of Operation

The pins with I^2C will be connected to the motor shield. The reason being is that there is not enough timers to control the five motors implemented in the project. The sensor will input a reference voltage in order to read the user. This voltage is read as analog and therefore must be changed to digital. In order to read this voltage the pin of use will have to have the capability of analog-to-digital conversion and be set to input in order to read the voltage.

4.1.2.2 Motor(s) Implementation

The following table measures the major positives and negatives as it pertains to each motor that we researched:

Motor	Pros	Cons
TowerPro MG995	Very powerful motor with high torque	Too heavy to use multiple motors in one arm
Hitec HS-85BB	Lightweight and affordable	Not powerful enough Bad reviews from users
Futaba S3150	Lightweight, powerful, Small dimensions	High price
Hitec HS-485HB	Affordable, enough torque for fingers	Too heavy Bad reviews
TowerPro MG930	High torque, lightweight, affordable	No reviews
Pololu Micro Gearmotor	Extremely small, good torque	Pricy, extra components be bought to make it work like a servo

Figure 79: Motor Comparison Table

We ultimately decided that the motor that had the pros completely away the cons was the TowerPro MG930. We plan on using three to five of these motors depending on what development issues or constraints we run into. The ideal situation would be five TowerPro MG930 servo motors running smoothly and controlling the movement of each finger separately. The index finger and thumb will absolutely have their own motors but the other three fingers are up for debate depending on what obstacles we face.

In order to implement these five motors into our arm we need a servo motor shield that allows us to control several motors at once since our MCU doesn't have enough PWM pins to control all five motors. We can use the Adafruit 16-channel PWM servo shield discussed which will be connect to four pins on the MCU. The only pins needed for the motor shield are ground, 5V supply, and two I2C control pins. If we need the I2C pins for any other devices they can still be used since they are a shared bus. As long as the components don't share conflicting addresses there should be no problem connecting them to the same I2C pins.

There are two power supplies on the shield. One is the VCC power supply, which is used for the 5V supply from the microcontroller to power the PWM chip. This determines the I2C logic level and the PWM signal logic level. If the power supply is connected correctly there will be a red LED lit which shows the MCU and servo shield are both working. The second power supply on the motor shield, labeled as the V+ power supply, is used to supply the power to the servos. Here we need to connect a second DC voltage supply of 5V and connect it through the blue terminal block on the shield. The servos we are using operate from 4.8V to 6V, so a 5V power supply will be enough. The servos will use a lot of power so it's not a great idea to use the 5V power pin from the MCU to power the servos as well. That could result in excess current draw and cause electrical noise, overheating, and erratic behavior in our MCU and motor shield.

If the power supply dips a lot we might need an electrolytic capacitor in the motor shield to make that voltage a bit more stable and protect our motors. The general rule for this shield is to use a capacitor that is n x 100uF, where n would be the number of motors being driven. In our case we might need to add a 470uF capacitor since we have five motors and generally you don't see 500uF capacitors out there. This is just a general value, we would have to take into account the servo's current draw, the motor's torque, and the stability of the power supply to get a closer value of the necessary capacitor.

The servos come with the standard 3-pin female connector which will be no problem connecting to the motor shield board. They plug directly into the headers on the PWM pins on the servo driver. Making sure we connect the ground wire to the bottom row on the servo shield and the signal wire to the top row on the shield, we do this for all five motors and should be good to go.

4.1.2.3 EMG Sensor Implementation

Stages necessary for EMG acquisition:

1) Electrodes
2) 1st Amplification
3) High-pass and Low-pass filters
4) 2nd Amplification
5) Low-pass filter
6) Analog-to-Digital Conversion (ADC)

Electrodes chosen for this project are standard disposable pre-gelled electrodes that are attached to the Shield-EMG-Pro Cable. They are easy to use and allow better contact with skin surface. They also allow direct connection to the computer and, therefore, easy testing with software.

1st Amplification stage requires differential amplifier with high input impedance and very low output impedance. **INA121** is an instrumentation amplifier that was chosen for the 1st Amplification. It is a low power, 3 op-am device with low bias current. Required gain can be set with one single resistor.

$$G = 1 + \frac{50\,k}{Rg}$$

$$Vo = G^*(V^+ - V^-)$$

The INA121 provides excellent rejection of high frequency common-mode signals. If the inputs are not properly balanced, common-mode signals can be converted to differential signals. That's why $V^+$and V^-connections should run directly adjacent each other, from the source signal all the way to the input pins. In our project we will use +5 V input source that will be used for both inputs to an instrumentation amplifier. Before connecting to the negative input it will be inverted by DC-inverter. All other noisy lines shouldn't be run near the inputs. The INA121's FET input circuitry provides low input bias current and high speed. It also achieves lower noise and higher accuracy with high impedance sources. Performance remains excellent with power supplies ranging from ±2.25V to ±18V.

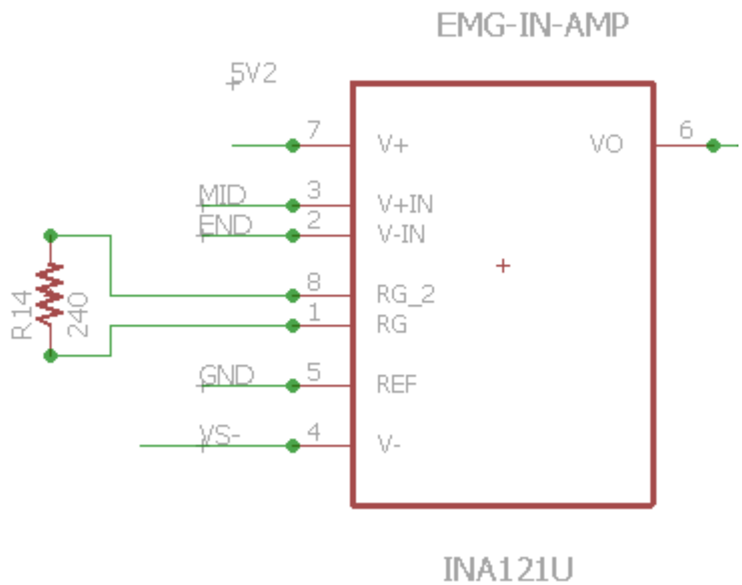


Figure 80: EMG Implementation - Instrumentation Amplifier

Filtering stage is achieved with 1st order low-pass and high-pass filters. We will also use diode rectifier to transform signal before it will go through second amplification. Diodes used are 1N4148.

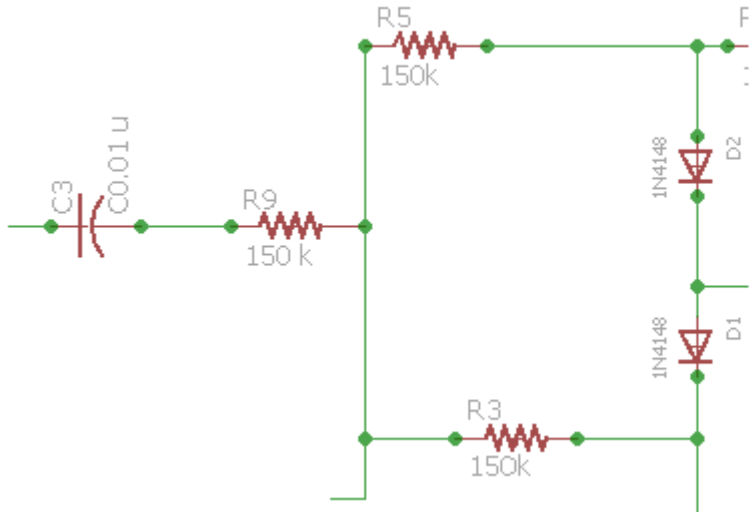


Figure 81: EMG Implentation - Filter and Diode Rectifier

2nd Amplification can be achieved with the help of a non-inverting amplifier. The non-inverting amplifier is only used when the signal is being received from a single wire referenced to ground. Amplification can be done in stages in order to cater for chip requirements, by cascading them in series. **TL084** with four built-in operational amplifiers was chosen to implement this stage. It features low-input bias and offset current with output short-circuit protection.

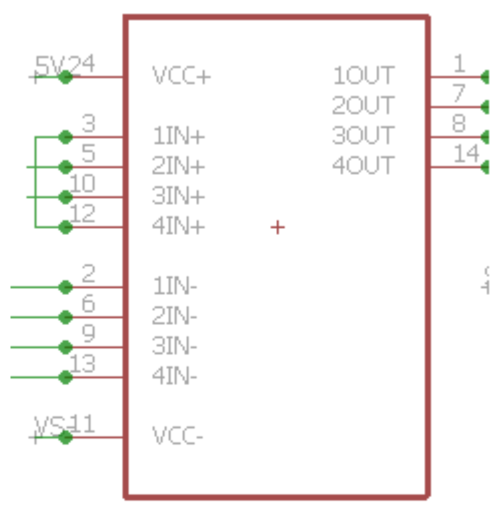


Figure 82: EMG Implementation - TL084 Operational Amplifier

Output filtering require simple 1st order low-pass filter.

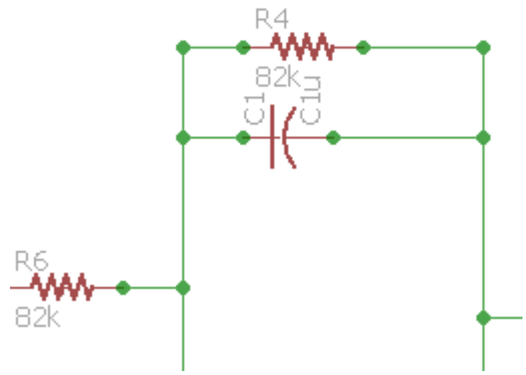


Figure 83: EMG Implementation - Output Low-Pass Filter

Analog-to-Digital Conversion (ADC) is not needed in EMG design since MSP430 used in this project already has it built-in.

Another option for designing EMG sensor is using by using **ADS1298** Analog Front-End from Texas Instruments. It is 8-channel, 24-bit low power ADC with built-in programmable gain amplifiers. Programmable gain is 1, 2, 3, 4, 6, 8, or 12. It allows multiple channel sampling that can be implemented in future designs. Due to time constraints this design would be a second choice and will only be implemented if overall design of the arm is successful before deadline.

4.1.2.4 Power Supply Implementation

Implementation of the power supply unit will be done in several phases. Considerations of all other parts of the project must be evaluated in order to power the components with correct supply voltages. The supply voltages of the system are listed below:

System Component	Supply Voltage
Motor: TowerPro MG930	4.8V-6V (Variation of Torque)
MCU: MSP430FR5969	1.8-3.6V (Recommended: 3.0V)
Sensor	5V

Figure 84: Power Supply Implementation - System Voltages

Using a 2-cell, 8.4V max Li-Ion battery, the power supply directly from the battery is performed first by using a buck-boost regulator to create a 5V supply rail supplying sufficient voltage to the sensor and motors. The supply rail is then regulated down to 3V for the MSP430FR5969 ultra-low power microcontroller using a linear regulator. Charging of the battery is performed by the Texas Instruments bq24103 charge management IC. The USB charging adapter supplies the bq24103 with around 5V, which is in range for this IC which requires a 4.35-16V input.

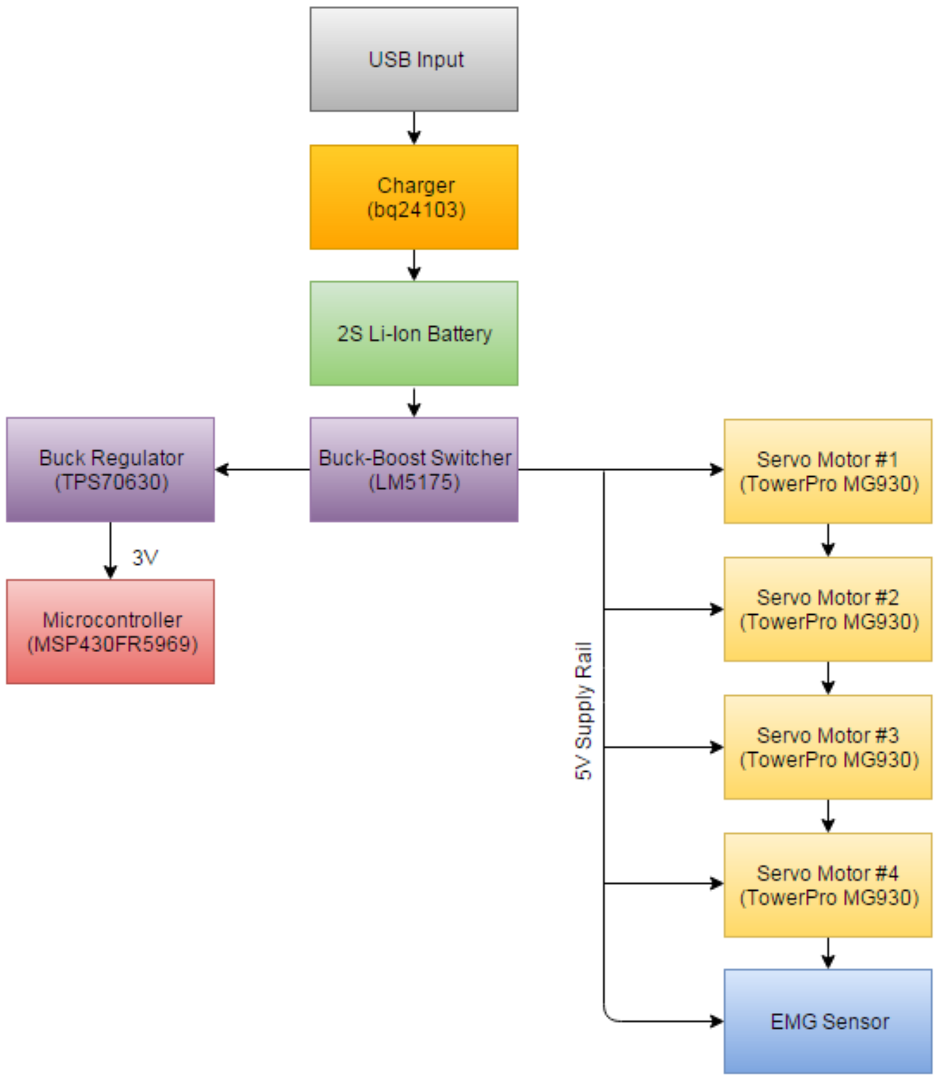


Figure 85: Power Supply Block Diagram

The potential current drain of each individual motor is not a heavy concern providing that the correct specifications are evaluated. However, in grips/gestures that require multiple motors to be operated once, a regulator the regulator must be chosen such that it handles the load. For example, the “Close-in” grip requires that all digits of the hand be actuated. To leave a wide enough margin, the current supply available to the motors is to be 1A each. The LM5175 Buck-Boost switcher was chosen such that that enough current is provided to the motors. The EMG sensor draws minimal current, as does the microcontroller.

4.2 Software

The use of software in this project will be programming the MSP430FR5969 microcontroller to take the input from the EMG sensor system and output the selected motor actuation. For execution of the motors, the software will exist in two “modes”.

Calibration Mode: The first mode, calibration mode, exists to calibrate the user’s voltage threshold from the EMG input. This is essential to provide a customized experience for the user, such that hardcoding specific voltage specifications are not required. After three flexions from the user, the calibration mode takes the average of these three voltage levels and specifies it at the voltage threshold.

Operating Mode: Operating mode exhibits the normal or “operating” state of this device after calibration. A predetermined threshold will be implemented for testing purposes and the calibration mode overwrites this threshold. The process is simple; the operating mode compares a new flex from the user to the threshold. This is such that no noise, small flexions, or an unwanted actuation performs on the device. Once the threshold is compared, if the recorded voltage level from the new flex is deemed higher or equal to the threshold, the selected motors will actuate. If lower, the device will not operate the motors.

4.2.1 Software Block Diagram(s)

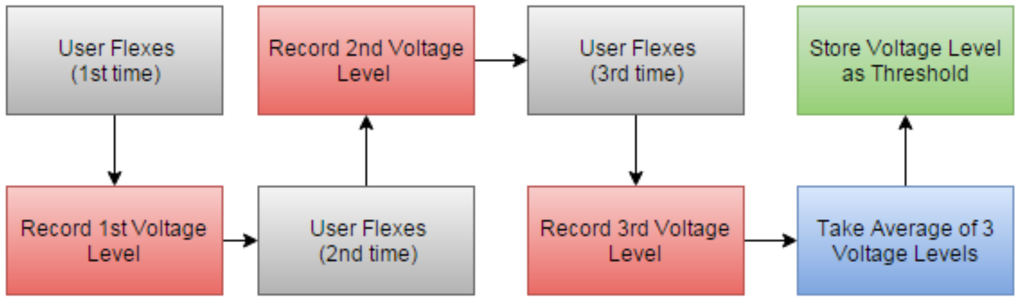


Figure 86: Calibration Mode

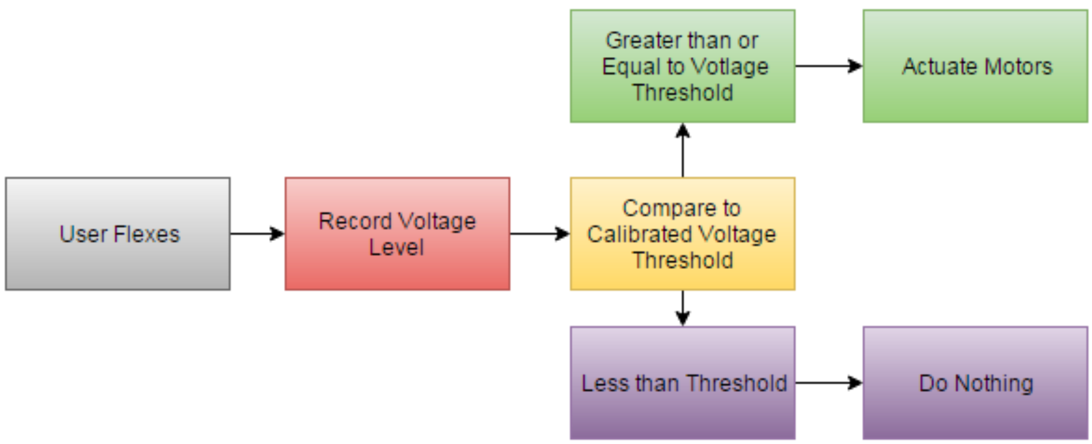


Figure 87: Operating Mode

4.2.2 Development Environment

There are a couple of options to begin programming the MSP430FR5969 from professional compilers to free versions. There is IAR Embedded Workbench Kickstart, Code Composer Studio, and MSPGCC. Below is a table explaining the differences between the three.

	Code size(free version)	Platform
IAR Embedded Workbench Kickstart	4KB	Windows
Code Composer Studio	16KB	Windows
MSPGCC	Unlimited	Linux and Windows

Figure 88: Comparison of IAR, CCS, and MSPGCC

For our project we will use Code Composer Studio. Code Composer Studio comes with a built in debugging interface

Software: The CPU in the MSP430FR5969 has 16 registers. The first 4 registers (R0-R3) have committed purposes. The rest of the registers (R4-R15) are working registers for general use.

R0	Program Counter
R1	Pointer Stack
R2	Status Register
R3	Constant Generator
R4-R15	General Purpose

Figure 89: MSP430FR5969 Committed Purpose Registers

There are certain registers that perform digital input and output operations. These include PxIN, PxOUT, PxDIR, PxREN, and PxSELx. PxIN is a read only value. When a pin is selected as input, reading the value of a bit tells the voltage on the pin. PxOUT is a writeable value.

When a pin is selected as output, the voltage can be changed by writing 0 or 1 to the conforming bit. PxDIR specifies whether a pin is an input or output. Each bit in the PxREN register disables or enables the pulldown or pullup resistor of the pin. Below is a table to show the proper values of PxDIR, PxREN, and PxOUT for I/O configuration.

PxDIR	PxREN	PxOUT	I/O Configuration
0	0	x	Input
0	1	0	Input with pulldown resistor
0	1	1	Input with pullup resistor
1	x	x	Output

Figure 90: Values for I/O Configuration

The function select registers (PxSEL0 PxSEL1) are used in order to choose what that specific pin is going to act as. If both of them are set to zero the function of the pin will be a general purpose input or output. If PxSEL1 is zero and PxSEL0 is one then the function is the primary module of that pin. If PxSEL1 is one and PxSEL0 is zero then the function is the secondary module. To continue, if both of the select registers are set to one then the tertiary module of the pin is the function chosen.

4.2.3 Coding

Analog-to-Digital Conversion: For this project, analog-to-digital conversion must be performed from the EMG input signal. The MSP430FR5969 supports 12-bit analog-to-digital conversion. In order to perform analog-to-digital conversion with the MSP430FR5969 we must first define the port pins that are capable and will be used as analog input channels. Below is a table with the pins from MSP430FR5969 that are capable of analog-to-digital conversion.

Pin number	Label
1	A0
2	A1
3	A2
4	A12
5	A13
6	A14
7	A15
9	A3
10	A4
11	A5
16	A8
17	A9
18	A10
19	A11
39	A6
40	A7

Figure 91: MSP430FR5969 ADC Pins

Next, a clock source needs to be selected. The source could either be from the conversion operation or set up with the Watchdog timer. For conversion operation there are four conversion modes (single channel single conversion, sequence of channels, repeat single channel, and repeat sequence of channels). Following, is the selection of the reference voltage, which for our project will be the voltage coming from the EMG sensor. After the reference voltage is selected, the sample and hold time is selected. The sampling time equates to a selected number of clock cycles. All of the pins that are capable of analog-to-digital conversion are also capable of performing other task, therefore after identifying the pin that will be used for conversion the analog-to-digital functionality of the pin needs to be turned on. All that is left is to take a reading and then set a program variable to the value after conversion.

Interrupts/Low-Power Modes: For this project, interrupts will be used to wake up the microcontroller in order to optimize battery consumption.

Mode	AM		LPM0	LPM1	LPM2
	Active	**Active, FRAM Off**	**CPU Off**	**CPU Off**	**Standby**
Maximum System Clock	16 MHz		16 MHz	16 MHz	50 kHz
Typical Current Consumption T_A=25°C	103 μA/MHz	65 μA/MHz	70 μA at 1 MHz	35 μA at 1 MHz	0.7 μA
Typical Wake-up Time	N/A		Instant	6 μs	6 μs
Wake-Up Events	N/A		All	All	LF I/O Comp
CPU	On		Off	Off	Off
FRAM	On	Off	Standby	Off	Off
High-Frequency Peripherals	Available		Available	Available	Off
Low-Frequency Peripherals	Available		Available	Available	Available
Unclocked Peripherals	Available		Available	Available	Available
MCLK	On		Off	Off	Off
SMCLK	Optional		Optional	Optional	Off
ACKL	On		On	On	On
Full Retention	Yes		Yes	Yes	Yes
SVS	Always		Always	Always	Optional
Brownout	Always		Always	Always	Always

Figure 92: MSP430FR5969 Low Power Modes – Part I

In the MSP430FR5969 interrupts play a significant role in enabling quick response, scalability, and recognition of infrequent occasions in code. Interrupts allow for detection of a button press or data being received. This is really important in this project because there needs to be a quick response when the user decides to perform a gesture coming out of low power mode. Interrupts cause the CPU to save its current state and proceeds to work through the interrupt function if one is present.

<table>
<tr><td rowspan="2">Mode</td><td>LPM3</td><td>LPM4</td><td>LPM3.5</td><td colspan="2">LPM4.5</td></tr>
<tr><td>Standby</td><td>Off</td><td>RTC only</td><td>Shutdown with SVS</td><td>Shutdown without SVS</td></tr>
<tr><td>Maximum System Clock</td><td>50 kHz</td><td>0</td><td>50 kHz</td><td colspan="2">0</td></tr>
<tr><td>Typical Current Consumption T_A=25°C</td><td>0.4 μA</td><td>0.3 μA</td><td>0.25 μA</td><td>0.2 μA</td><td>0.02 μA</td></tr>
<tr><td>Typical Wake-up Time</td><td>7 μs</td><td>7 μs</td><td>250 μs</td><td>250 μs</td><td>1000 μs</td></tr>
<tr><td>Wake-Up Events</td><td>LF
I/O
Comp</td><td>I/O Comp</td><td>RTC I/O</td><td colspan="2">I/O</td></tr>
<tr><td>CPU</td><td>Off</td><td>Off</td><td>Reset</td><td colspan="2">Reset</td></tr>
<tr><td>FRAM</td><td>Off</td><td>Off</td><td>Off</td><td colspan="2">Off</td></tr>
<tr><td>High-Frequency Peripherals</td><td>Off</td><td>Off</td><td>Reset</td><td colspan="2">Reset</td></tr>
<tr><td>Low-Frequency Peripherals</td><td>Available</td><td>Off</td><td>RTC</td><td colspan="2">Reset</td></tr>
<tr><td>Unclocked Peripherals</td><td>Available</td><td>Available</td><td>Reset</td><td colspan="2">Reset</td></tr>
<tr><td>MCLK</td><td>Off</td><td>Off</td><td>Off</td><td colspan="2">Off</td></tr>
<tr><td>SMCLK</td><td>Off</td><td>Off</td><td>Off</td><td colspan="2">Off</td></tr>
<tr><td>ACKL</td><td>On</td><td>Off</td><td>Off</td><td colspan="2">Off</td></tr>
<tr><td>Full Retention</td><td>Yes</td><td>Yes</td><td>No</td><td colspan="2">No</td></tr>
<tr><td>SVS</td><td>Optional</td><td>Optional</td><td>Optional</td><td>On</td><td>Off</td></tr>
<tr><td>Brownout</td><td>Always</td><td>Always</td><td>Always</td><td colspan="2">Always</td></tr>
</table>

Figure 93: MSP430FR5969 LPM Specifications – Part II

To active the different low power modes individual bits in the status register are changed.

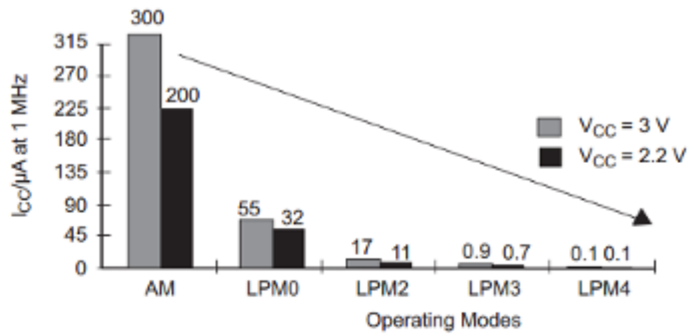


Figure 94: LPM Power Consumption (Reprinted with permission from Argenox)

Programming FRAM: FRAM will be used in this project in order to store and update the code. FRAM has practically indefinite write endurance and does not have need of a pre-erase in which every write to FRA is non-volatile. Downfall to FRAM is that wait states are required if the CPU is accessing the FRAM at speeds larger than 8 MHZ. Code Composer Studio™ is used to partition the memory for program code, variables, stacks, and constants depending on the application. Both program code and constant data will be apportioned in FRAM. Variables are generally stored in the SRAM of the MCU. If the variable size is too large to fit in the SRAM, C-language #pragma directives can be used to distribute specific variables or structures in FRAM memory.

4.3 PCB

For this project, the microcontroller, power supply, EMG sensor, and any other extra peripherals will be mounted on a printed circuit board (PCB). This will be realized soldering surface mount components manually or via a pick and place machine and reflow oven. A PCB is comprised of a number of layers usually with a top layer of silkscreen which denotes part numbers and symbols as well as underlying solder mask and copper. Traces are used as “wires” or conductors to provide channels between the different components. The number of layers within a PCB is determined by the about of copper sections. One-Sided boards contain only one copper layer, whereas double or multiple-sided PCBs contain more than one. Design of the PCB is realized by a number of different electronic design automation (EDA) programs: namely EagleCAD and Atlium Designer.

4.3.1 Manufacturer/Ordering

There are multiple options in the market for printed circuit boards (PCB). We could possibly go with a single sided PCB, which has just one copper layer; another option is a double-sided PCB, which contains two copper layers; and finally a multi-layer PCB, which is comprised of both outer and inner layers. The multi-layer PCBs are often preferred since they allow for much higher component density including conductors on different layers. These conductors can be connected with plated through holes called vias.

In the process of looking to get a PCB board printed we can either find a manufacturer online or print the circuit board ourselves. Seeing as the development of a PCB can get quite complicated and none of the group members have prior experience with this method, we will definitely go the manufacturer route and purchase our PCB online. It is imperative that we compare prices, location, and delivery time of our PCB manufacturing options. One thing almost all of the main manufacturers have in common is that they accept many types of file formats, meaning we can utilize any software design program when creating our PCB design.

4.3.1.1 OSHpark

OSH Park is a community PCB order. This means that in order to reduce production cost and essentially cost to the consumer they print your PCB board together with other PCB boards from different customers. They ship their product out of Oregon and provide the option of free shipping which would take 1-5 business days. When ordering two-layer boards it includes three copies of our designed board and costs $5 per square inch. If we decided to go with a four-layer board instead it would also include three copies of our board but the price would double to $10 per square inch and the manufacturing process and shipping would take a little longer as well.

4.3.1.2 Advanced Circuits

Advanced Circuits, also known as 4PCB, has a very cheap and quick delivery method for when you need your PCB right away. They offer next day shipping with no solder mask for $35 and a per inch cost. There is also a student offer where you get a 60 square inch board with solder mask and top silkscreen for

$33 and $50 after shipping. This company has very good reviews in respects to quality and cost. Usually when buying in bulk it can result in being a cheap option and is the way to go, but for an individual PCB it may not be the best choice. They have two divisions where they ship from; one is Arizona and the other is Minnesota.

4.3.1.3 PCB-Pool

PCB-Pool is from a company called Beta LAYOUT in Germany. Obviously the fact that it would be international shipping will increase the cost and time of delivery for our PCB design. The positives about this manufacturer are the great reviews from hobbyists in terms of the quality of the product. Depending on whether we order a two-layer or four-layer board the price can go anywhere from $45 to $105 plus shipping.

4.3.1.4 Electronic Interconnect

Electronic Interconnect is based out of Illinois, which of course is always a plus to buy domestic in terms of delivery time and cost. They have a bit better reviews from customers than Advanced Circuits and actually sell PCBs per piece. When ordering a per piece PCB, they only offer two-layer and four-layer and have a fixed price of $25. The delivery time is seven days, which seems like an average delivery time for domestic manufacturers after researching several options.

After comparing and contrasting the aforementioned printed circuit board manufacturers and weighing their pros and cons we collectively decided to order our PCB from Electronic Interconnect. After going through several engineering forums we could see that this company, based out off Illinois, has very good reviews from previous customers. The reason PCB-Pool wasn't chosen was the fact that they're located in Europe and it was going to bring the cost and time of delivery to a level that was inconvenient for our budget and schedule.

The other three companies, OSH Park, Advanced Circuits, and Electronic Interconnect, were all pretty evenly viewed by our group; but essentially the great reviews and the fact that they sell PCB per piece at a fixed rate made Electronic Interconnect seem like the right choice. In the community forums there were several customers that complained about Advanced Circuits' quality of product and even mentioned the fact that they had received several faulty PCBs from them. These same customers went on to say that after switching to Electronic Interconnect they didn't have the same problems and all of their PCBs were functioning properly. For these reasons along with the affordable price we decided to choose this route in PCB manufacturing.

4.3.2 Design

CadSoft EAGLE: For this project, CadSoft EAGLE (also known as EagleCAD) will be chosen as the preferred design method due to its presence as an industry standard. CadSoft EAGLE is an industry leader when it comes to EDA programs. Cadsoft EAGLE offers a variety of features such as DesignLink which enables the user to search within a parts database and generate a comprehensive Bill of Materials (BOM). EagleCAD contains two design areas: a schematic editor and a layout. The schematic enables us to provide an overview of the design, seeing how all of the components are connected. Many EagleCAD schematics are listed on the manufacturer's website for a certain part, which is another reason why it is the selected EDA for this project. The layout editor represents a visual of the actual printed circuit board itself; laying out the locating of all the components within a physical space. Maneuvering between the two editors is done by the "Switch-to-board"/"Switch-to-schematic" button. Tracing between the components can either be performed manually or via the Autorouter tool. The Autorouter tool automatically routes the best path and traces between components, and can be guided manually by the input of certain factors. Because of these features and popularity of the software, CadSoft EAGLE is the EDA program of choice for this design.

5 Project Assembly

Assembly: Assembly of the arm begins with the housing. The electronic components fit in a suited, customized housing for each individual. This housing includes the battery and electronic components including the microcontroller and sensor system. The motors will be included in the hand close to the fingers for actuation. The outside casing is modeled in a 3D-modeling program, such as Solidworks and Blender. This casing will be printed in a Stratasys Dimension Elite 3D-printer located in the University of Central Florida manufacturing lab. The Multiplex Bionic will be printed in Acrylonitrile Butadiene Styrene plastic several other portions of the product.

5.1 Prototype

Prototyping will be performed through simulation software such as Multisim. Following the schematic on mutism and CadSoft EAGLE, the board layout will be drawn. The components will be purchased in the form of through hole to allow for prototyping and testing. Individual components as well as evaluation modules (EVMs) and booster packs will be considered. These devices will allow us to directly test the components before ordering the final PCB. Prototyping of the MSP430FR5969 microcontroller will be delivered via the MSP-EXP430FR5969 Launch Pad Evaluation Kit. Each of the sub-systems will be built on separate breadboards to ensure that faulty board does not impact the overall schematic.

5.2 Testing

Testing essential to make sure the *Multiplex Bionic* is foolproof and remains intuitive to the user. The testing will begin with testing the major sub-sections of the system itself, which is the Microcontroller, Motor(s), EMG Sensor, and Power Supply. There will also be an over-arching test plan that is designated into three phases.

Phase 1	Test Individual Hardware Components
Phase 2	Test Combinational Hardware Components
Phase 3	Test Entire System (Prototype)
Phase 4	Test Entire System (PCB)

Figure 95: Testing Plan Phases

Phase 1 consists of testing each of the major subsections of the system. This is the initial step and is enacted to ensure that all components are in working condition. The individual test plans of each of these components are detailed in the next sub-sections of this report.

Phase 2 consists of combining different components together. The most simple of this will begin by combining the battery and power supply system up to the microcontroller and a single motor. After actuation of one motor is performed and drainage of the battery is examined, multiple motors will be added. Eventually, the EMG sensor will be implemented to combine with the rest of the system as the input device.

Phase 3 consists of testing the entire prototype system. This system will be implemented on a solder less breadboard and/or soldered proto board. After testing of this phase is complete, the PCB will be ordered and subject to final testing.

Phase 4 is the testing of the final finished printed circuit board. This is the board that will go into the final product and must be tested thoroughly. If problems arise from this testing phase, changes in design and/or manufacturer must be considered.

5.3.1 Microcontroller Test Plan

To begin testing, the microcontroller will need to be powered by a computer through the LaunchPad and the USB cable provided. The evaluation module or LaunchPad comes with out of box software preloaded onto it. When the "out of box" demo powers up, the red and green LEDs will toggle several times indicating proper implementation of the demo. Next, the MSP430FR5969 will enter low power mode 3 awaiting UART commands from the computer user interface. Now that the MCU works by being powered by the computer it is time to make sure the MCU will work "battery free" meaning with the super capacitor provided on the LaunchPad powering the system as the LaunchPad is still connected to the computer. The steps to charge the super capacitor the computer are listed in the table below.

1	Set jumper J10 to "Debugger" position
2	Set jumper J2 to "Use" position
3	Set jumper J11 to "Charge" position
4	Set "V+" jumper J13
5	Connect the LaunchPad to computer using USB cable
6	Allow super capacitor to charge for at least 2 minutes maximum of 3 minutes
7	Remove "V+" jumper J13

Figure 96: MSP430FR5969 - Charging Super Capacitor

Once the super capacitor is fully charged the LaunchPad will be able to be powered up and a menu will appear on the computer screen. The “Battery Free” option on the menu will be selected. Within the “Battery Free” option there is a ‘Display Mode’ where when you press switch 2 the device will be put into low-power mode 3.5. Next, the battery chosen for the project will be connected to the external input to power the MCU. With the batteries full charge the MCU will be put into each low-power mode until the batteries are drained. This is going to test the longevity of the batteries with everything idle. This is to test the functionality of the different low power modes. With the servos and display connected, and batteries fully charged the whole system will be “turned on” to test how long the batteries last with everything on. The display will be in constant use and the servos in constant rotation. Several test programs will be ran to test the microcontroller’s functionality, and that it is in proper working condition.

5.3.2 Motor(s) Test Plan

In order to test our servo motors we need to remember what the purpose of our project is. We want to build an arm that has a hand capable of making three or four gestures. This means our motors must properly actuate the fingers on the hand in order to perform these hand gestures.

Motor Characteristic	Testing Pass/Fail Criteria
Dynamic Torque	Powerful enough to move the fingers
Holding Torque	Powerful enough to hold the fingers in a locked position without fidgeting
Rotation	Able to rotate finger at least 90 degrees towards the palm
Power Efficiency	Seeing how much power is consumed and for how long at full load
Accuracy	Programming the motor to rotate to a certain angle and having it be within 10% accuracy of the desired position
Sensitivity	Measuring angular rotation output for different input voltages

The load being tested on the motors is the load of one finger on the Limbitless arm. We will be able to perform eye tests on the motor to make sure it is functioning properly. If it is able to withstand the load of a finger both to move it and to hold it in a bent position after it has been pulled then it will have passed the torque tests. The rotation test is to make sure that the motor is completely pulling the finger to the position that is desired for any given gesture, which should be at least 90 degrees movement from resting position to bent position.

Failing the dynamic torque test would mean that the motor is not powerful enough to actuate the fingers, meaning that when the motor is running the fingers sit still and don't move. Failing the holding torque test would mean that the motor has enough torque to move the fingers but once it is asked to hold that load steady in one spot it becomes unstable. In both cases it would show that the motor is not powerful enough and a servo with higher torque is needed. Finally, failing the rotational test would mean that the servo doesn't have enough angular rotation both clockwise and counterclockwise to let the load reach the positions desired. In this case a new motor would also be needed.

The accuracy test is one of the most important for our motors because we don't want a servomotor that does not rotate to the correct angle when being told to do so. When making the different hand gestures this becomes a very important factor because if the angle positions are accurate enough our hand will not have the correct functionality and purpose. A loose estimate would be to have the angle position accuracy to come within at least 10% of the desired output, anything more would be unacceptable.

Between testing of the motors, stress tests will be performed to ensure proper operation. Testing of the current draw at full load will also be a necessity such that it doesn't over-drain the battery. Multiple servos will be attached to the battery at varying loads and the battery drain will be noted

5.3.3 EMG Sensor Test Plan

EMG Sensor Testing must be done in two stages:

- Simulation
- Prototyping

EMG circuitry has to be simulated before prototyping. The optimal software would be Multisim by National Instruments. If desired output is not achieved, each part of EMG circuitry has to be simulated separately to make sure that it satisfies all design requirements: 1st Amplification Gain = 5, 2nd Amplification Gain = 1000, and all undesired noise is removed during both stages of filtering.

If simulation was successful, prototyping can be completed. Each part of circuitry must be tested separately to assure that all components work properly. Digital multimeter and oscilloscope are needed to confirm the magnitudes and the shape of signal during prototyping. Additional software for testing EMG signal may be used to compare the raw input signal with the one expected.

5.3.3 Power Supply Test Plan

The power supply testing will begin with the battery implementation. The battery at first will be connected to a load to test the discharging conditions. The time at which the battery is discharged when the load is applied will be compared with the battery's capacity. The protection circuit will also be tested. Implementing the charger on a breadboard, the protection of the battery will be evaluated by attempting to overcharge and over discharge the voltage past the limits of the over-voltage protection and under-voltage protection of the charger. Testing the battery without the protection circuitry will also be implemented, to evaluate the effect on the battery if the protection circuitry malfunctions.

After the battery is fully tested and deemed reasonable to use for the project, it will be connected to the rest of the system in this project. The voltage being delivered to each component will be measured. The current being drawn from each sub-system will also be evaluated. More specifically, the current draw from the motors will be measured when idle and under varying loads. If the current being drawn under any circumstance is over 1A, different motors or power supply options must be considered.

6 Administrative Content

This portion of the report is for administrative content including but not limited to: Group Dynamics/Labor Division, Milestones, and Cost/Budget.

6.1 Group Dynamics

Team:

- Arian Garcia
    - Major: Electrical Engineering
- Javier Morales
    - Major: Electrical Engineering
- Tatsiana Smahiluk
    - Major: Electrical Engineering
- Christopher Vendette
    - Major: Electrical Engineering

Division of Labor: The project is organized in to four major hardware component subsystems: Sensors, Motors, Microcontroller, and Power. These subsystems were divided amongst the group members in order to maximize efficiency. Due to some of the work being more difficult than others, collaboration between each of the hardware systems is sometimes necessary. Listed below is the specified major design role divided for individual.

Design Role	Member(s)
Power Supply	Christopher Vendette
USB Charging	Christopher Vendette
Microcontroller	Arian Garcia, Javier Morales
Display	Arian Garcia
Motors	Javier Morales
Sensors	Tatsiana Smahliuk

Figure 97: Project Role Division

Arian Garcia will be responsible for selection and programming of the microcontroller. This includes the analog-to-digital conversion of the EMG input as well as interfacing the display and notification LEDs. Testing of the microcontroller as well as implementation of low-power roles will also be a major obligation.

Javier Morales will be responsible for all motor implementation in this project. This includes the selection, comparison, and testing of different motors. Along with this role he will be working with Arian Garcia on programming of the microcontroller. More specifically, he will be in charge of the programming of the motors and different gestures/grips.

Tatsiana Smahiluk will be responsible for all sensor implementation in this project. This includes the EMG sensor system as well as any other sensor considerations. Tatsiana will also be in charge of the sensor placement, and research into different methods of switching between gesture selections. She will also be collaborating with Christopher Vendette in design and manufacturing of the PCB. She is in charge of the finances, bill of materials, and budget considerations.

Christopher Vendette will be in charge of designing the power supply unit for the system. Duties include testing of the power supply as well as the implementation. With inclusion of the power supply, the most effective charging process will also need to be considered. Design of the PCB through EagleCAD as well as manufacturing and ordering will be a specified responsibility. This responsibility also requires testing of the PCB itself. Christopher will also be in charge of overseeing the integration connection of all major subsystems.

6.2 Milestones

Following are the milestones, or goals wish to be achieved by the relative time frame. This is for purpose of organization and group productivity and is listed in chronological order.

Fall 2015 (Research Phase):

- Select MCU/Components
- Design Board Schematic
- Simulate Board Schematic
- Build Prototype Board
- Test Prototype Board
- Design PCB Layout

Figure 98: Project Research Milestones

Spring 2016 (Development Phase):

- Test PCB Layout
- Manufacture Mechanical Housing & Components
- Integrate Board into Mechanical Housing
- Assbemble Completed Product
- Troubleshooting
- Presentation

Figure 99: Project Development Milestones

These milestones will be completed over the course of two full semesters at the University of Central Florida. The research phase is used to search for components, research similar projects, and formulate the initial project document. The group used this time to accumulate as much useful information regarding implementation of the electronic system within the *Multiplex Bionic* limb. The development phase serves to build upon this knowledge through the use of the development of the device itself.

6.3 Cost

Budget is planned to be kept around $500-750. During the manufacturing process additional expenses may occur due to design change and/or additional materials cost. Budget for servos is $100 but can be increased up to $200 in order to get the best product that will satisfy size and weight constraints. Design of more efficient EMG and charger circuitry may require additional spending.

Also, shipping costs that may occur while purchasing parts are not included since rates vary due to vendor and/or manufacturer.

Component	Quantity	Price
ABS P400/P430	1 cartridge	265.00
Microcontroller	1	30.00
Servo(s)	4-5	100.00
Battery	1-2	10.00
Charger	1	1.00
DC Inverter	1	0.75
Voltage Regulators	2	5.00
EMG sensor	1	35.00
EMG cables	1	20.00
EMG electrodes	1 box	20.00
Misc. mechanical parts	1	25.00
Misc. electrical parts	1	50.00
Total	**17**	**561.75**

Figure 100: Estimated Cost

Miscellaneous electrical parts: Miscellaneous electrical parts include resistors, amplifiers, capacitors, inductors, and diodes.

Miscellaneous mechanical parts: Miscellaneous include everything that cannot be 3D printed.

3D printing for this project is provided by Limbitless Solutions' 3D printer located in the University of Central Florida manufacturing laboratory.

7 Appendices

This section will include permissions and references used for content in this report.

7.1 References

"10 Beginner MSP430 Tutorials and Counting." FourThreeOh. Web. 30 Sept. 2015.

A.O. Andrade, S. Nasuto, P. Kyberd, C.M. Sweeney-Reed, F. Van Kanijn, EMG sig-nal filtering based on empirical mode decomposition, Biomed. Signal Process.Control 1 (1) (2006) 44–55.

"Adafruit 16-Channel 12-bit PWM/Servo Shield - I2C Interface." *Adafruit*. Web. 28 Nov. 2015.

"Adafruit Pro Trinket - 5V 16MHz." Adafruit Industries Blog RSS. Web. 1 Dec. 2015. <https://www.adafruit.com/product/2000>.

"Arduino Playground - Throb." Arduino Playground - Throb. Web. 20 Nov. 2015.

"Atmel 8-bit Microcontroller with 4/8/16/32KBytes In-System Programmable Flash." Web. 1 Dec. 2015. <https://www.adafruit.com/datasheets/ATMEGA328P.pdf>.

Backman, Michael. "Anorad Ironcore and Ironless Linear Servo Motors." *Rockwell Automation*. Web. 9 Nov. 2015.

Carlo J. De Luca (2006) “Electromyography: Encyclopedia of Medical Devices and Instrumentation” (John G. Webster Ed.), John Wiley Publisher.

Carlo J. De Luca (2002) “Surface Electromyography: Detection and Recording”, Delsys Incorporated.

Claudio Castellini and Patrick van der Smagt. 2009. Surface EMG in advanced hand prosthetics. Biological cybernetics 100, 1 (2009), 35–47.

Datasheet ADS1298 “Low-Power, 8-Channel, 24-Bit Analog Front-End for Biopotential Measurements” Texas Instruments Incorporated.

"Digital Servos." *Futaba®*. Web. 29 Nov. 2015.

"DisplayMate LCD Advantages and Disadvantages." DisplayMate LCD Advantages and Disadvantages. Web. 8 Dec. 2015.

E. Niedermeyer, F. H. Lopes da Silva. 1993. Electroencephalography: Basic principes, clinical applications and related fields, 3rd edition, Lippincott, Williams & Wilkins, Philadelphia.

"HS-485HB Deluxe HD Ball Bearing Standard Servo." *Hitec Multiplex*. Web. 29 Nov. 2015.

"HS-85BB Premium Micro Servo." *Hitec Multiplex*. Web. 28 Nov. 2015.

Igoe, Tom. "DC Motor Control Using an H-Bridge." *ITP Physical Computing*. 31 Aug. 2014. Web. 20 Nov. 2015.

K. Englehart, B. Hudgins, M. Stevenson, and P.A. Parker, “A dynamic feedforward neural network for subset classification of myoelectric signal patterns,” Engineering in Medicine and Biology Society, 1995, IEEE 17th Annual Conference, 2002, pp. 819–820.

K. Englehart, B. Hudgins, P.A. Parker, M. Stevenson, “Classification of the myoelectric signal using time-frequency based representations,” Medical Engineering & Physis, 21 (6-7),1999, pp. 431-438.

"KENTEC ELECTRONICS KTBCD430-D1. Alphanumeric LCD Display, 2.8 V, Reflective." KTBCD430-D1. Web. 30 Nov. 2015.

"Kentec QVGA Display BoosterPack." - BOOSTXL-K350QVG-S1. Web. 30 Nov. 2015.

Lievendag, Nick. "The Creative’s 3D Printing Filament Guide: ABS vs PLA vs Many New, Innovative Materials." 30 Oct. 2014. Web. 20 Oct. 2015.

M. Paceli, L. Caldani, R. Paradiso “Textile Piezoresistive Sensors for Biomechanical Variables Monitoring” *Proceedings of the 28th IEEE, EMBS Annual International Conference*, New York City, USA, Aug 30-Sept 3, 2006, pp. 5358-61.

"MSP430FR5969 (ACTIVE)." MSP430FR5969. Web. 8 Oct. 2015.

"MSP430 FRAM Technology-How To and Best Practices." Web. 28 Nov. 2015. <http://www.ti.com/lit/an/slaa628/slaa628.pdf>.

Musslih LA. Harba and Goh Eng Chee (2002) “Muscle Mechanomyographic and Electromyographic Signals Compared with Reference to Action Potential Average Propagation Velocity”, Engineering in Medicine and Biology Society, 19th Annual International Conference of the IEEE, Vol.3.

P. Konrad, The ABC of EMG: A Practical Introduction to Kinesiological Electromyography, Version 1.0, Noraxon, 2005.

"Pervasive Displays - EPD BoosterPack / Extension Kit." Pervasive Displays – EPD BoosterPack / Extension Kit. Web. 30 Nov. 2015.

"Pololu - 1000:1 Micro Metal Gearmotor." *Pololu: Robotics & Electronics*. Web. 28 Nov. 2015.

Printed Circuit Boards - PCB Manufacturer USA - Electronic Interconnect. Web. 2 Dec. 2015.

S Day. 2002. Important factors in surface EMG measurement. Technical Report. 1–17 pages. http://www.andrewsterian.com/ courses/214/EMGn measurement and recording.pdf

"Serial Peripheral Interface Bus." Wikipedia. Wikimedia Foundation. Web. 8 Nov. 2015.

"Serial Peripheral Interface (SPI)." Serial Peripheral Interface (SPI). Web. 12 Oct. 2015. <https://learn.sparkfun.com/tutorials/serial-peripheral-interface-spi>.

"The Technique." *PCB-Pool*. Beta Layout. Web. 2 Dec. 2015.

"TI LaunchPad." - BoosterPacks. Web. 28 Nov. 2015. <http://www.ti.com/ww/en/launchpad/boosterpacks.html?DCMP=mcu-launchpad&HQS=boosterpacks>.

"TMS320F28027 (ACTIVE)." TMS320F28027. Web. 30 Nov. 2015. <http://www.ti.com/product/TMS320F28027>.

"TowerPro MG930 Servo." *RC Servo Specifications and Reviews*. Web. 28 Oct. 2015.

"TowerPro MG995 Servo." *RC Servo Specifications and Reviews*. Web. 28 Nov. 2015.

"UNDERSTANDING THE FCC REGULATIONS FOR COMPUTERS AND OTHER DIGITAL DEVICES." Web. 11 Nov. 2015. <https://transition.fcc.gov/Bureaus/Engineering_Technology/Documents/bulletins/oet62/oet62rev.pdf>.

"USB." Wikipedia. Wikimedia Foundation. Web. 2 Dec. 2015.

"Use an Arduino to Control a Motor." *All About Circuits*. 3 June 2015. Web. 23 Nov. 2015.

Web. 1 Dec. 2015. <http://www.ti.com/lit/ug/slau535b/slau535b.pdf>.

Web. 19 Nov. 2015. <http://www.ti.com/lit/ds/symlink/tms320f28075.pdf>.

"What's The Difference Between DC, Servo & Stepper Motors?" *Mod My Pi*. 25 Aug. 2013. Web. 7 Nov. 2015.

7.2 Permissions

AG Arian Garcia

To: info@argenox.com;

Tue 12/8/2015 3:30 PM

Hello,

My name is Arian Garcia. I am an electrical engineering student at the University of Central Florida. Currently, I am working on a Senior Design project and i would like permission from you to use "Power consumption profile of the various LPMs" in my document from the website: http://www.argenox.com/library/msp430/msp430-interrupts-and-low-power-chapter-7/

This table will not be modified neither published, it will only be used for educational purpose.

Thank you in advance for your time. Your permission will be greatly appreciated.

Arian Garcia
University of Central Florida
Electrical Engineering Student

Gustavo Litovsky <gustavo@argenox.com>

To: Arian Garcia;

Tue 12/8/2015 3:31 PM

Inbox

You replied on 12/8/2015 3:36 PM.

Hi Arian,

No problem. Thank you for asking. My only request is if you can link back to the original page.

Best Regards,

Gustavo Litovsky
Argenox Technologies
www.argenox.com

Permission to use picture from datasheets

Arian Garcia

To: univ@ti.com;

Tue 12/8/2015 4:23 PM

Hello,

My name is Arian Garcia. I am an electrical engineering student at the University of Central Florida. Currently, I am working on a Senior Design project and i would like permission from you to use these 4 images:

"Pin diagram-RGZ Package-MSP430FR596x and MSP430FR596x1" http://www.ti.com/lit/ds/symlink/msp430fr5969.pdf
"EVM Overview" http://www.ti.com/lit/ug/slau535b/slau535b.pdf
"2802x 38-Pin DA TSSOP (TOP VIEW)" http://www.ti.com/lit/ds/symlink/tms320f28027.pdf
"PM, PAG, RTD PACKAGE (TOP VIEW)" http://www.ti.com/lit/ds/symlink/msp430f147.pdf

These pictures will not be modified neither published, it will only be used for educational purpose.

Thank you in advance for your time. Your permission will be greatly appreciated.

Arian Garcia
University of Central Florida
Electrical Engineering Student

Senior Design: Permission to Use Image

Javier Morales

To: comarketing@nxp.com;

Reply all

Wed 12/9/2015 1:16 PM

Hello,

My name is Javier Morales. I am an electrical engineering student at the University of Central Florida. Currently, I am working on a Senior Design project and I would like permission from you to use "Fig 1. Block diagram of PCA9685" from the PCA9685 data sheet found at http://cache.nxp.com/documents/data_sheet/PCA9685.pdf?pspll=1.

This figure will not be modified, it will only be used for educational purpose.

Thank you in advance for your time. Your permission will be greatly appreciated.

Javier Morales
University of Central Florida
Electrical Engineering Student

Senior Design: Permission to Use Image

Javier Morales

To: inbox@pololu.com;

Reply all

Wed 12/9/2015 1:36 PM

Hello,

My name is Javier Morales. I am an electrical engineering student at the University of Central Florida. Currently, I am working on a Senior Design project and I would like permission from you to use "1000:1 micro metal gearmotor" image found at https://www.pololu.com/picture/view/0J3410

This figure will not be modified, it will only be used for educational purpose.

Thank you in advance for your time. Your permission will be greatly appreciated.

Javier Morales
University of Central Florida
Electrical Engineering Student

Senior Design: Permission to Use Image

DH **Derrill Hartley <derrill@pololu.com>**
To: Javier Morales;

Reply all | Wed 12/9/2015 3:49 PM

Hello, Javier.

Thank you for your inquiry. You are welcome to use that picture with proper attribution.

Please let me know if you have any additional questions.

Sincerely,
Derrill Hartley
(702) 262-6648
www.pololu.com
....
Pololu Corporation
920 Pilot Rd.
Las Vegas, NV 89119
USA

Rockwell Automation
Contact Us

Our Company

Contact Us
- Overview
- Pricing
- Technical Questions

Resources
- Find Your Local Distributor
- Find Your Local Sales Office
- Technical Support

Use the contact form below to submit your questions or comments.

Email Address: javiermorales@knights.ucf.edu

Verify Email Address: javiermorales@knights.ucf.edu

Question or Comment: My name is Javier Morales. I am an electrical engineering student at the University of Central Florida. Currently, I am working on a Senior Design project and I would like permission from you to use "Figure 1. Linear Motor" found at http://www.rockwellautomation.com/resources/downloads/rockwellautomation/pdf/anorad/Comparison_WhitePaper.pdf

SUBMIT CLEAR

Senior Design: Permission to Use Image

JM Javier Morales

To: customerservice.towerpro@gmail.com;

Reply all

Wed 12/9/2015 2:28 PM

Hello,

My name is Javier Morales. I am an electrical engineering student at the University of Central Florida. Currently, I am working on a Senior Design project and I would like permission from you to use the image of the TowerPro MG995 found at http://www.towerpro.com.tw/product/mg995-robot-servo-180-rotation-2/

This figure will not be modified, it will only be used for educational purpose.

Thank you in advance for your time. Your permission will be greatly appreciated.

Javier Morales
University of Central Florida
Electrical Engineering Student

Senior Design: Permission to Use Image

JM Javier Morales

To: copyrightcounsel@list.ti.com;

Reply all

Wed 12/9/2015 4:05 PM

Hello,

My name is Javier Morales. I am an electrical engineering student at the University of Central Florida. Currently, I am working on a Senior Design project and I would like permission from you to use the image of the pin configuration for the bq24230 found on page 5 of the bq24230 data sheet http://www.ti.com/lit/ds/symlink/bq24230.pdf

This figure will not be modified, it will only be used for educational purpose.

Thank you in advance for your time. Your permission will be greatly appreciated.

Javier Morales
University of Central Florida
Electrical Engineering Student

Contact Us

First Name *

Tatsiana

Last Name *

Smahliuk

Email *

tatsianavus@gmail.com

Phone Number

Subject *

Permission to use webp

What are you interested in? *

EEG Biosensor Solutions

Message

Florida. I'm currently working on my Senior
Design project and I would like to ask your

Silicon Valley Headquarters

NeuroSky, Inc.
125 S Market St – #900
San Jose, CA 95113
(408) 200-6675 (General VM / No Support Inquires)

Tatsiana V <tatsianavus@gmail.com> 2:34 PM (19 minutes ago)
to delsys

Hello,

My name is Tatsiana Smahliuk. I'm an electrical engineering student at University of Central Florida. I'm currently working on my Senior Design project and I would like to ask your permission to use pictures of your sensor from webpage http://www.delsys.com/products/desktop-emg/surface-emg-sensors/

Thank you for your time, and I greatly appreciate your help.

Sincerely,

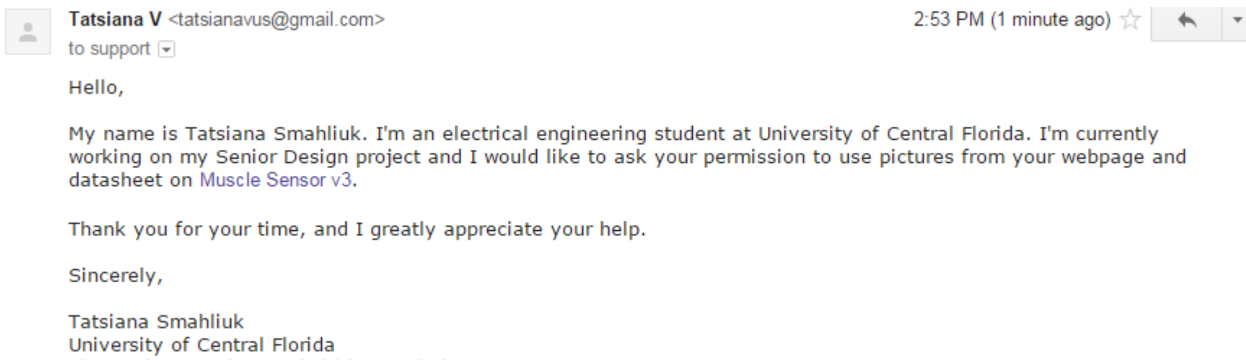
Tatsiana Smahliuk
University of Central Florida
Electronics Developer, Limbitless Solutions.

Devi Bheemappa <devi@delsys.com> 2:48 PM (5 minutes ago)
to me

Pls go ahead.

Devi Bheemappa
V.P Sales and Marketing

508-545-8200 (P) 508-975-4551 (F) sales@delsys.com - (e) www.delsys.com - (w)



Tatsiana V <tatsianavus@gmail.com>

to support

2:53 PM (1 minute ago)

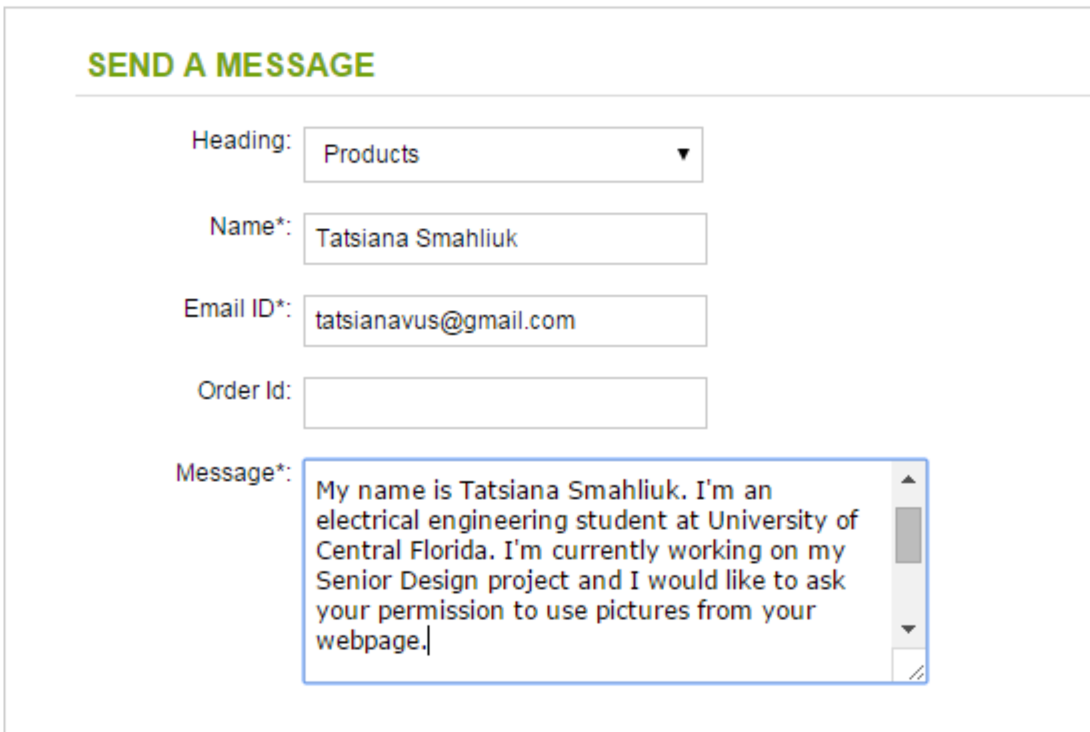
Hello,

My name is Tatsiana Smahliuk. I'm an electrical engineering student at University of Central Florida. I'm currently working on my Senior Design project and I would like to ask your permission to use pictures from your webpage and datasheet on Muscle Sensor v3.

Thank you for your time, and I greatly appreciate your help.

Sincerely,

Tatsiana Smahliuk
University of Central Florida



SEND A MESSAGE

Heading: Products

Name*: Tatsiana Smahliuk

Email ID*: tatsianavus@gmail.com

Order Id:

Message*: My name is Tatsiana Smahliuk. I'm an electrical engineering student at University of Central Florida. I'm currently working on my Senior Design project and I would like to ask your permission to use pictures from your webpage.