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Developing 3D Printed Prosthetic Hand Model Controlled by EMG Signal from Forearm

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The objective of this Bachelor thesis was to make a 3D printed prosthetic hand which is controlled by forearm muscles to make palm close and open. The goal of this project is to help the patients who have lost their hand in accident, disease or birth defects.

The prosthetic hand is attached to the patient's forearm to replace their lost hand. Hand will be controlled by reading signals from forearm using three EMG electrodes that are attached to forearm. Fingers and palm are separate movement achieved with 6 motors, five motors for each finger and one for wrist movement. Force sensor are added to prosthetic palm finger tips to provide feedback to main MCU for motor control.

The first and main task to be solved by conducting this research is to build a device helping the patient to have a prosthetic hand which can be controlled to perform simple daily tasks for example grabbing and releasing objects, since commercial solutions provided cost from 5000 to 10 000 Euros for cosmetic arm and even more for mechanical. Since the device will be attached in the patient’s forearm, the design need to be light and the size needs to be suitable to attach in the patient forearm.

Keywords	Electronics, Biomedical, EMG, Prosthetics hand

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List of Abbreviations

EMG	Electromyography
MUAP	Motor Unit Action Potential
SPI	Serial Peripheral Interface
MCU	Microcontroller unit
PLA	Polylactic acid
ABS	Acrylonitrile Butadiene Styrene
TEFLON	Polytetrafluoroenthylene
PCB	Printed circuit board
IC	Integrated circuit
MOSFET	Metal-oxide-semiconductor field-effect transistor
LBI	Low battery indication
DC	Direct current
PCB	Printed circuit board
LED	Light emitting diode

1 Introduction

The project has been created in partnership with Ngoc Tiep Nhu Nguyen with a focus on reading EMG signals from upper hand and signal processing. The prosthesis is an artificial device designed to provide some functionally of lost limbs in an accident or caused by decease. In this project the upper extremity amputation is considered.

The number of amputation in developing countries are significantly higher than in western countries. Reasons for it is of lack either medical knowledge, equipment or medicine for sicknesses that are defeated in developed countries. The concrescences from limb amputation ranges from psychological to economical and physical disability. To minimize these consequences the artificial limbs are created. There are many companies producing prosthetics. Some have only aesthetics function but other tries to restore some functionally of lost limb to help with grabbing objects or other activities. Despite number of different mechanical design, control mechanisms and power sources. In both cases, aesthetic only and mechanic functional, these devices are very costly, from hundreds to thousands of euros. This is one of reasons why only 5% of people can afford to have prosthetics in developing countries, other reasons are distribution and maintenance. The main goal of the project is to create low cost 3D printable and easy to assemble prosthetic hand. The figure 1 shows standard model of myoelectric hand functionality.

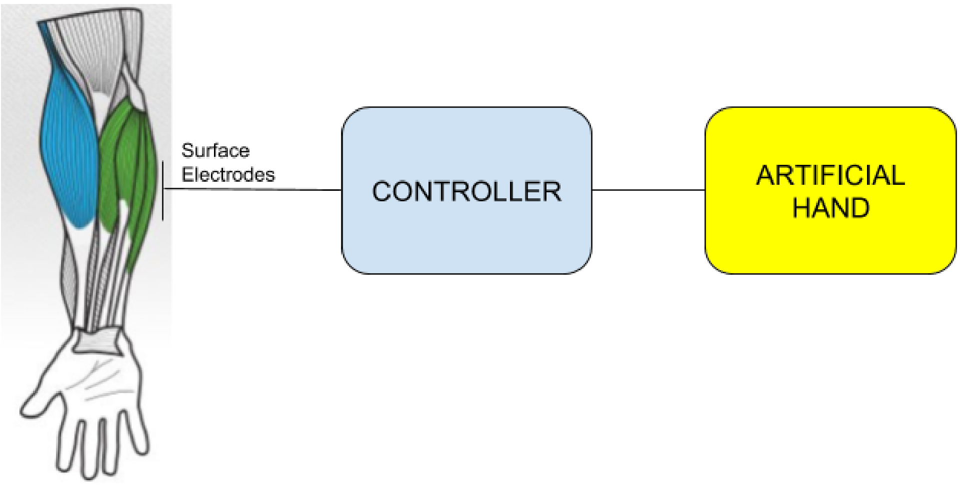


Figure 1 Myoelectric hand [3]

The myoelectric sensors pick up signals generated in the muscle tissue that are amplified filtered and undergo signal processing to control artificial hand. Advancements in the 3

D printing technology has allowed to decrease in price of 3 D printers and used materials. Not only lower price but presence of open source community has allowed designers to create not only simple but also complex in functionality prosthetics

In this thesis the object is to create 3D printable hand whose fingers are individually controlled for closing or opening hand using five motors for fingers and moving wrist controlled by single servo motor. Included force sensors allows for better capability of object holding. The goal is to help people to carry out simple daily tasks and restore some capability of lost limb.

2 Background Research

Prosthetics are artificial devices designed to replace a lost body part, for example a hand or a leg, which may be lost in an accident, trauma, disease or birth defect. There are several types of prosthetics such as aesthetic, which is meant to look like lost limb but not providing functionality; myoelectric, which is a body-controlled prosthetic with some sort of sensor, and an activity specific prosthetic designed for certain activity, for example, spring type leg for running, hook for holding boat paddle etc.

Myoelectric prosthetics have advantage of aesthetics and functionality. Myoelectric prosthetics is using electromyography signal generated by muscle contractions [4]. By placing sensors on forearm, the patients can learn how to voluntarily contract specific muscle groups to activate the prosthetic palm to close fingers or wrist. There are two main ways how to attach prosthesis to patients, first using sockets that are usually made of hard epoxy resins and fiberglass or carbon fibers [5]. To make interfacing more comfortable to patient, inner part of socket usually has some sort of lining made of silicon or other materials. Socket and lining are usually made by casting mold of the patient’s stump, the part of the body where prosthetic will be attached, customizing socket individually for each patient [6]. A second way is to use direct bone attachment, this method inserts a titanium rod into patient bone at the end of stump.

There are some advantages and disadvantages for each method, for example, socket may cause pain to the patient, but direct to bone method cannot handle as much load as socket prosthetics can, due to risk of shattering bone [5].

2.1 Human Anatomy

It is necessary to understand human hand anatomy and the structure to design aesthetically realistic looking and realistically functional prosthetics. Therefore, understanding of human hand anatomy is important. The human wrist, thumb and hand is complex. It consists of many different parts, six different joints, two different muscles groups, three different nerves types, and bones [7]. For this project the only bone structure is analyzed as prosthetics is made from solid material and no soft tissue simulation was attempted. The human hand consists of 27 bones, divided in three groups. These groups are called carpals, metacarpals and phalanges. The wrist part of hand is made of bone cluster called carpals, this group is considered part of wrist and is responsible for forward and backward movement of the wrist. Figure 2 shows bones of human hand.

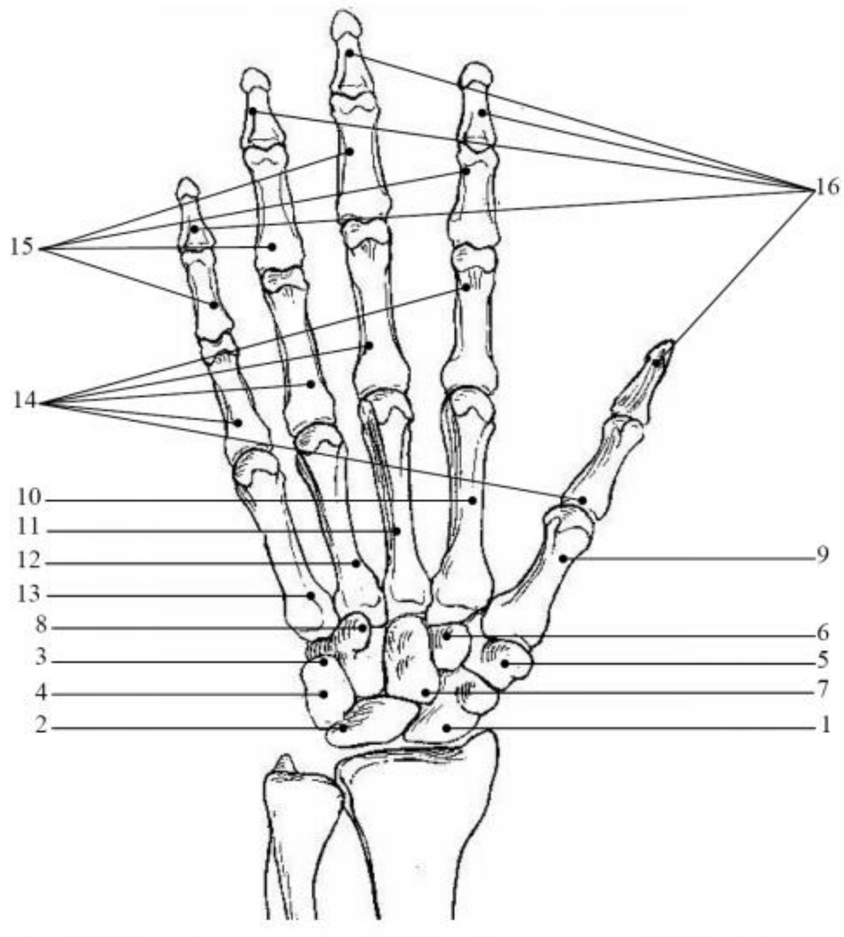


Figure 2: Skeletal structure of the human hand. Carpals:1. Scaphoid, 2. Lunate, 3. Triquetrum, 4. Pisiform, 5. Trapezium, 6. Trapezoid, 7. Capitate, 8. Hamate [7].

The central part of hand which is called palm, consist 3 of 5 bones. This group is called metacarpals. These bones are visible in Figure 2. Bone group from nine to thirteen. 9. First metacarpal (Thumb), 10. Second metacarpal (Index finger), 11. Third metacarpal (Middle finger), 12. Fourth metacarpal (Ring finger), 13. Fifth metacarpal (Little finger) The last group is called phalanges and it consists of fourteen bones. These bones form fingers visible in figure 3.

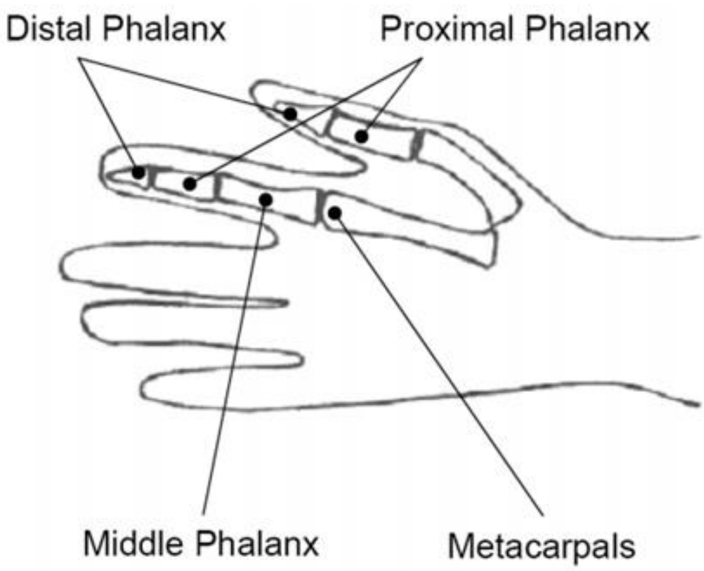


Figure 3: Phalanx bones of the human hand [7].

2.2 EMG Signal

EMG stands for electromyography. It is the study of electrical signals in a muscle. It is often referred to as myoelectric activity. Muscle tissue conducts electrical potential similar way to the nerve cells. The name given to these signals is muscle action potential. The muscle is composed of bundles of specializes cells capable of relaxation and contraction. The main function of these cells is to produce motion, moving substance within body, providing stabilization and generating heat. The three muscle tissue types can be identified on basis of structure, contractile properties and control mechanisms, these are called skeletal muscle, smooth muscle and cardiac muscle. The study of EMG signal is applied to skeletal muscle group. The skeletal muscle tissue is attached to the bones and is responsible for moving and supporting skeleton. The contraction in muscle are initiated by impulses in the neurons to the muscle and it is usually volunteer action. The skeletal muscle fibers are filled with neurons for contractions. These neurons provide stimulation to the muscles and is called motor neurons. The human body generally is neutral, it has the same amount of positive and negative charges. In the resting state, the nerve cell membrane is polarized due to difference in the concentration of ionic compositions around the membrane. The potential exists between inner and outer cellular fluids of the cells. A muscle fiber depolarizes in the response to a stimulus from a neuron, as a signal propagates along surface of the fiber it causes fiber to twitch. This depolarization together with movement of ions generates electric field near each muscle fiber. A EMG signal is the train of Motor Unit Action Potential (MUAP) showing the muscle response to neural stimulation [35].

The EMG signal amplitude range is 0-10 mV before amplification and main dominant energy is in a rage from 0-500 Hz. The EMG signal acquire noise while propagating through different tissue. Electrical noise that affects EMG signal is categorized into: Inherent noise in electronic equipment, ambient noise, motion artefact and inherent instability of signal.

All electronics equipment generate noise, it is Inherent noise in electronic equipment, it cannot be eliminated but reduced by using better components and design techniques. The electromagnetic ambient noise may have one to three times higher amplitude than EMG signal. There are two main reasons for motion artifacts. Those are electrode interface and electrode cable. The motion artifacts can be minimized by proper design of electronic circuitry and set-up. Inherent instability of signal is produced by random nature of EMG signal. The source of it is motor unit firing rate that is in frequency range of 0 to 20 Hz.

The factors mainly affecting EMG signal are also categorized into categories in to Causative factors, Intermediate factors and Deterministic factors. The classification of these factors is important for EMG signal analysis algorithm optimization and equipment design. Causative factors directly affect EMG signal and is caused by electrode structure, shape, distance between electrodes, location with respect to muscle, anatomical, biomedical factors like blood flow, fiber diameter. Intermediate factors are physical and physiological phenomena influenced by one or more causative factors. Reasons for it can be bandpass filtering nature of the electrode probes, crosstalk from nearby muscles. The deterministic factors are influenced by intermediate factors, such as the number of active motor units and their firing rate and mechanical interaction between muscle fibers.

To improve quality of EMG, the signal to noise ratio should be highest possible. The distortion of EMG signal must be as small as possible and no unnecessary filtering should be performed. During EMG signal processing only, positive values are analyzed in half wave rectification method and all negative data is discarded but in full wave recitation method absolute vales of each data point is used. Preferred method if full wave rectification.

3 Hardware Design of Prosthetic Hand

The hardware consists of a physical 3D printed hand, MyoWare muscle sensors, several modified servo motors, and main control board**.** The control board combines power circuitry, motor drivers, main microcontroller, and other circuitry that is necessary for various functions. For this project it was chosen to use a popular MyoWare muscle sensor [12]. This sensor is relatively cheap and has integrated features that help to minimize hardware design. MyoWare muscle sensor provides easy integration with microcontrollers. It has been specifically designed for use with a MCU by utilizing single-supply voltage in range of +3.1 V min to +5 V max, raw EMG output, reverse polarity protected power pins, indicator LEDs, and an On/Off switch. Not only does it provide raw EMG signal, but an integrated amplifier and signal integrator provide already processed signal which allows to use a less powerful MCU.

3.1 3D Printed Hand Palm Section Design.

The goal of this project is to create a prosthetic hand for a patient who has lost his or her hand. Visually most anatomically correct hand model was criteria for choice of using Flexy hand. This model of hand is second iteration of prosthetic hand that has been created by Steve Woods. There are many other 3D printed hand models freely available, however most of them look robotic and do not look like human hand. Steve Woods is the founder of company called Gyrobot Ltd and he has created the hand (figure 4) that looks realistic [13]. This hand model was chosen because it represents human hand anatomy most accurately.

Decision to use open source hand model was to save time as it take considerable time to create realistic model. Emphasis in this project is on electronics hardware design and not on 3D modeling. However, this model needed to be considerably modified. The original model is meant for mechanical actuation. The finger closing action is actuated by bending wrist itself. This action will close the fingers.

Figure 4: Original flexy hand [13].

Bending the wrist will close all fingers at the same time, forming fist. For this project it was necessary to design a new attachment to the patient's upper hand which, is called the stump. This part of the prosthetic hand also had to include a wrist motor, electronics and batteries. These parts of the model are just a representation of an attachment mechanism as in real life application would be uncomfortable for the patient. Each patient has a unique physiology of the stump and a unique gauntlet would be made for each patient. With inexpensive 3D printing technology, it is possible to print new prosthetics and gauntlets every few months. This is especially useful for kids that would outgrow prosthetic in short amount of time.

The 3D printed parts have some very useful features over some traditional methods like casting or CNC machining, such as the possibility to change internal structure of printed parts. This is achieved by creating honey comb filling in the parts that would be either completely hollow or solid. Honey comb filling makes parts stronger but slightly heavier than completely hollow parts. Printing completely solid part would make parts very rigid but much more heavy, resulting to more heavier hand. Figure 5 shows process of finger printing and the internal structure of the parts.

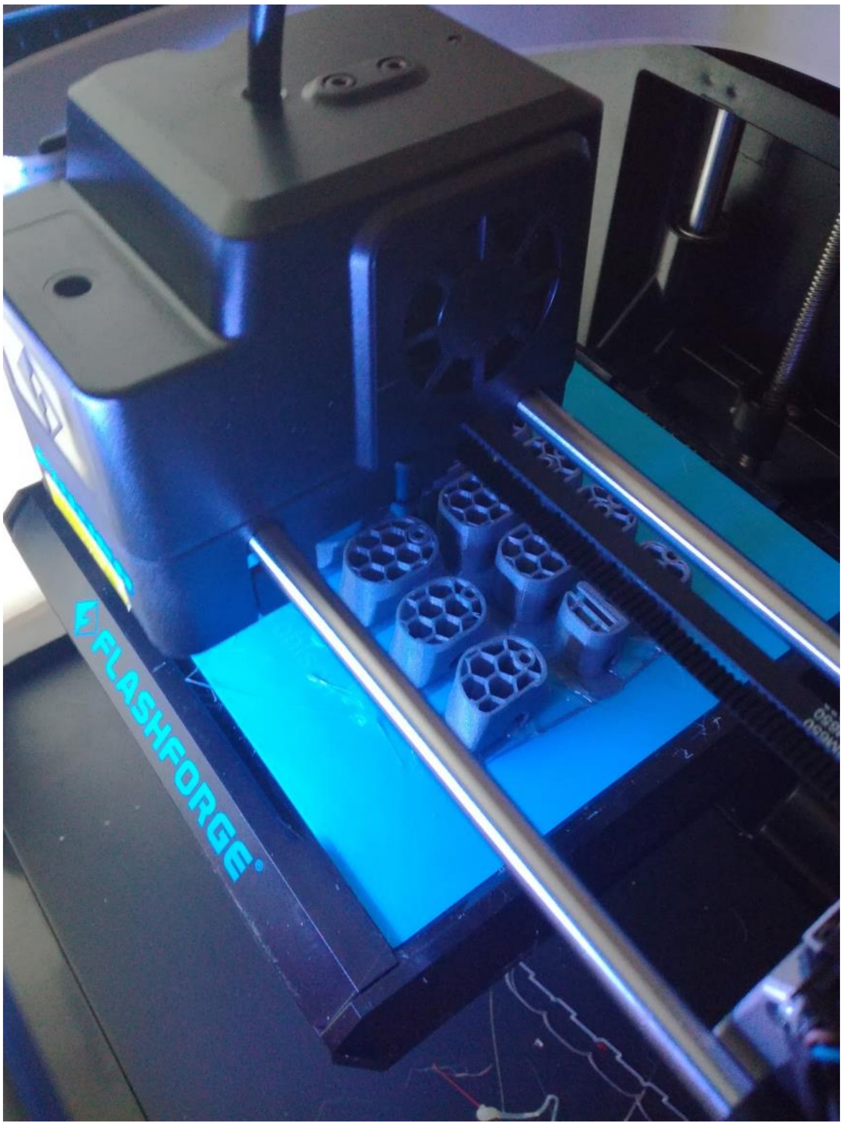


Figure 5: Finger parts with honey comb style filling.

The possibility to adjust and modify internal structure of printed parts is very useful feature in printing technology. It is possible to achieve most suitable configuration for the task. For example, young child probably does not need to have very strong rigid and therefore much more heavy hand, but adult person may need much more rigid hand and it can be heavier.

3D printing technology allows the use of different materials, such as PLA, ABS, TEFLON and many more. Different plastics with different additives, like carbon fibers, will have different properties [14]. For this project it was chosen to use PLA plastic. Polylactic Acid (PLA) is different than most thermoplastic polymers in that it is derived from renewable resources like corn starch or sugar cane. Therefore, it is environmentally friendly [15]. The finger joints have been printed with flexible filament. The manufacturer has not provided any specification of polymer used to produce elastic 3D printer filament [16].

3.2 Finger Actuator Servo Motor Modification

For finger actuation, it was chosen to use small hobby servo motors. These motors provide a few necessary features:

- Small size
- Light weight
- Integrated gearbox

In the figure 6 is an image of a servo motor used in the project.

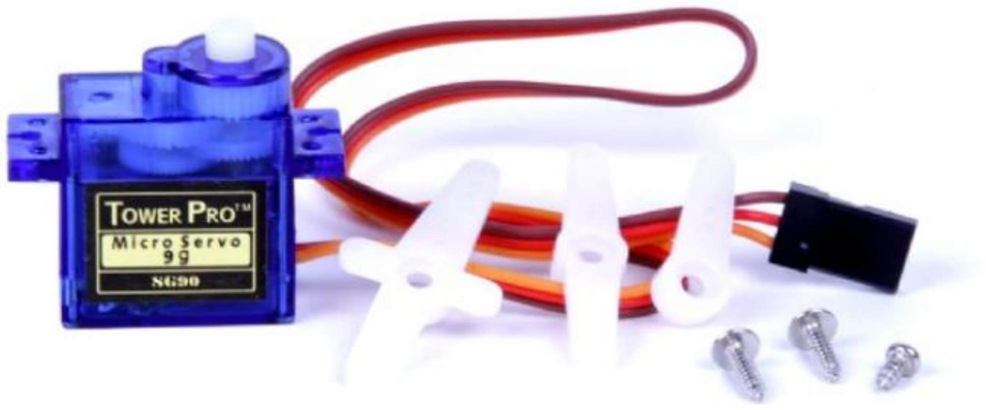


Figure 6: SG90 servo motor [18].

However, servo motors also have some features that are undesired in this specific use case, that were necessary to modify. Servo motors are designed for specific degree rotation. For this servo motor model rotation is limited to 180 degrees; 90 degrees in each direction. This is achieved with a hardware limit in gearbox and feedback potentiometer [17]. The needed modifications for the servo motor where continuous rotation and new feedback loop.

3.2.1 Continuous rotation modification.

To achieve continuous rotation of the servo motor, it was necessary to completely disassemble and perform these modifications to the gearbox,

- remove physical stop wedge from gear
- remove potentiometer

The gear has half shaft hole that is attached to potentiometer shaft to provide a feedback signal. This hole was drilled to full circular hole. This modification disengages gear from the potentiometer feedback shaft and removal of the wedge figure 7 A in the red circle allows full uninterrupted continuous rotation by keeping all original gearbox parts. Figure 7 A shows gear before it has been modified. Figure7 B shows gear after it has been modified. The potentiometer itself was not removed as it is integrated into body of gear-box assembly and some of the gears are sharing its shaft, but potentiometer circuitry was removed as it did not provide continues rotation feedback.

Figure 7: Gearbox before (A) and after (B) modification.

3.2.2 Continuous rotation modification feedback.

Continuous feedback has been achieved by replacing original potentiometer of the servo motor with a rotary encoder. Rotary encoder is electromechanical device (a type of position sensor) used in several applications from elevators to robotics and consumer electronics. Coupled with motor drives they provide position and rotation speed information by tracking motor shaft rotation. There are many different types of rotary encodes, and they are classified either by output signal or sensing technology. In the figure 8 is shown classification of the rotary encoders.

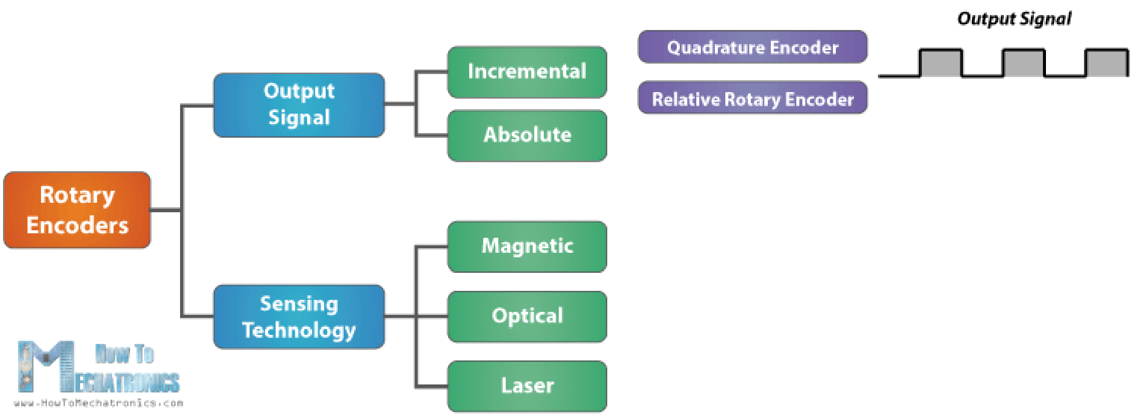


Figure 8: Rotary encoder classification diagram [36].

In this project incremental rotary encoder is used. In the figure 9 is shown a basic concept of how incremental encoder generates pulses. The disk has evenly spaced contact zones that are connected to common pin C. and two separate signal contact points A and B, visible in figure 9.

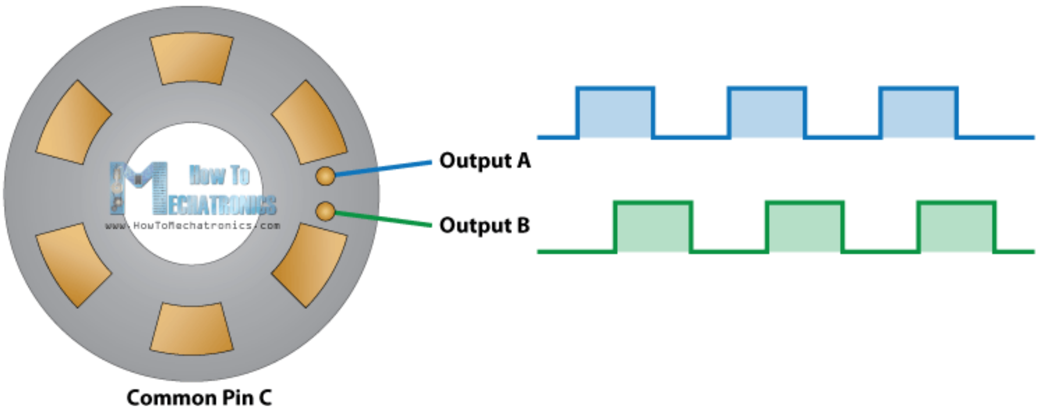


Figure 9: Rotary encoder pulse generating concept [36].

When the disk starts rotating, common pin C will contact A and B pins periodically and this will generate two square waves. To determine rotation any of two signal pins can be used just by counting pulses on the pin. For direction detection we need to consider both signal pins at the same time. Notice in figure 9 that output signal on A and B pins are out of phase. In figure 10 is an example of determining rotation direction based on digital signal value.

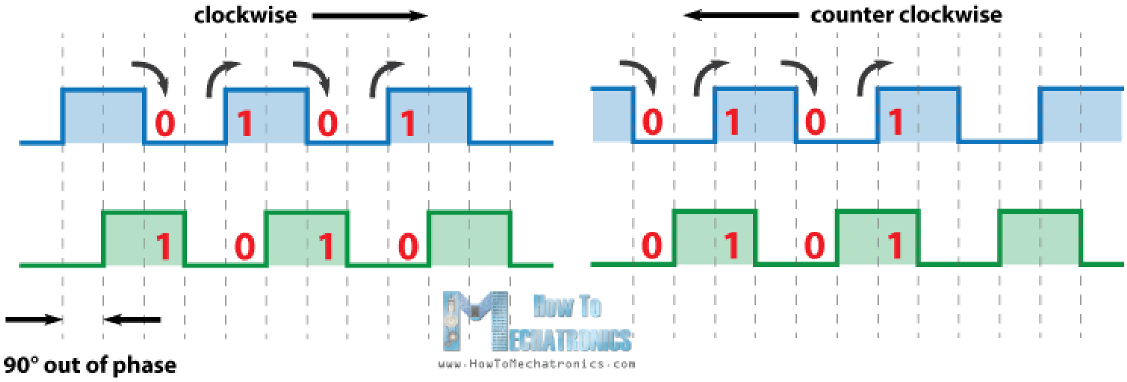


Figure 10: Example of determining rotation direction [36].

For example, if steps are counted each time the signal changes, from high to low or low to high, the two signals have opposite values and we say it is clockwise direction. Vice versa if the encoder will be rotating counter clockwise the signal will have same value. By considering this, it is easy to program MCU to determine the rotation direction and speed.

Figure 11 shows chosen rotary encoder for this project. The choice for this encoder was dictated by physical size of palm. The larger encoder would not have space to fit current model of the palm. The dimension of this encoder is 10 mm in length and width, and 2.2 mm in high. Shaft hole diameter is 4 mm.

Figure 11: Rotary encoder used in the project [31].

In the figure 12 is a developed circuit to generate signals from rotary encoder. R1-B and R1-A are output signals from rotary encoder that are fed in to a MCU digital pins providing High and Low signal levels.

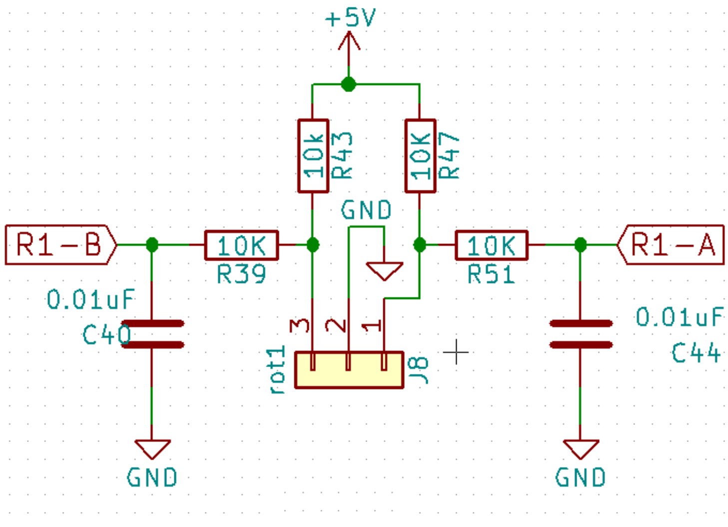


Figure 12: Rotary encoder circuit.

The rotary encoder is not physically present on PCB but is placed in front of the motor located in a palm. Connection between rotary encoder and circuit on PCB is made by wires that are connected to J8 connector (figure 12).

3.2.3 Servo arm replacement.

The servo motor has an attachable arm on an output shaft from the gearbox and this arm is visible in the figure 6. This arm provides a possibility to attach different attachments to a servo motor. However, in this case the arm's swing has a large radius and is not suitable for compact design. Not only that but arc is not long enough to close fingers of prosthetic hand completely. The modification was made by removing the servo arm and 3D printing a pulley (figure 13). Furthermore, actuator string will be wound on pulley allowing fingers to close in tighter grip. In the figure 14 is shown the servo motor after modification with a new pulley and the removed potentiometer. There is a servo driver integrated circuit board still visible which was removed later.

Figure 13: Modified servo motor.

In the final assembly there has been one more addon to the modified servo motor. This addon is coupling shaft from the pulley to the rotary encoder The Figure 14 shows the test fitting motor into an assembled hand and the finished modification to the servo motor.

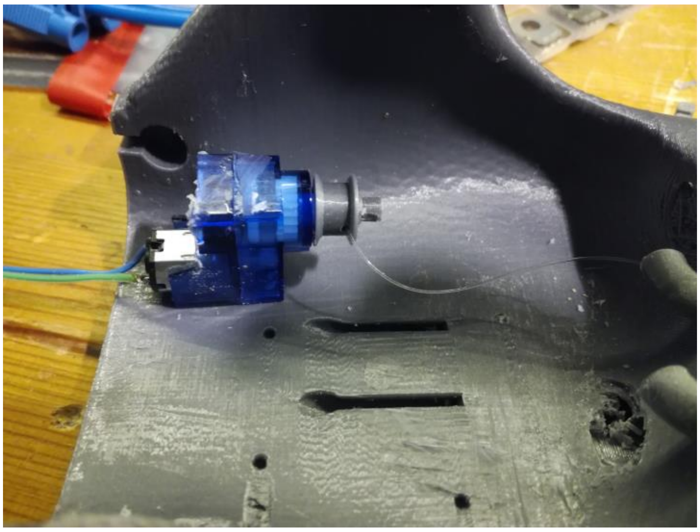


Figure 14: Test fitting motor assembly.

3.3 Gauntlet Design.

It was necessary to design a new gauntlet. It can be seen in the Figure 3 that the original gauntlet has not been designed for the motorized function of the prosthetic hand. A new gauntlet, figure 15, has been designed to host the wrist actuator motor and hinge.

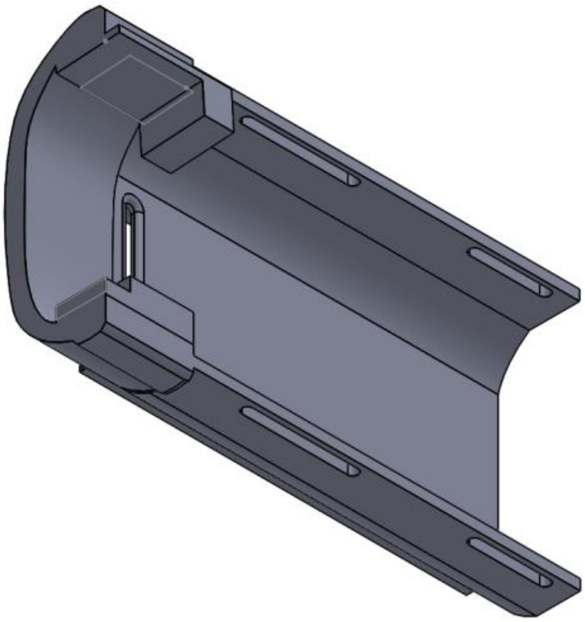


Figure 15: Custom Gauntlet.

3.4 Hand Mechanics Assembly.

The first part of the assembly belongs to the fingers. The fingers are assembled by sliding flexible joint pieces in part which is replacing the Phalanx bones of hand. The Figure 16 (A, B, C, D, E) demonstrate assembly process.

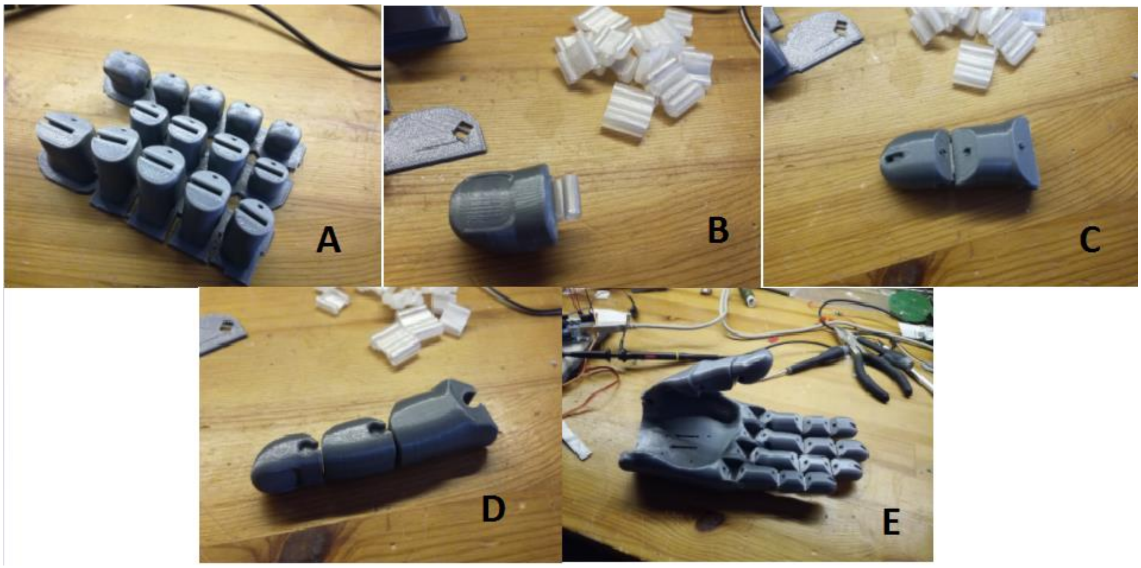


Figure 16: Hand assembly Process

The white pieces represent flexible joints. These pieces not only function as hinges but also provide finger return to straightened position. After the tension on string that is closing hand is released. The original model assembly for the wrist, follows same procedure, that is using flexible joint pieces to attach hand to the gauntlet. For the new gauntlet that includes a wrist actuator motor it is necessary to have a solid hinge mechanism. All parts have been 3D printed and attached to gauntlet. Additionally, some smaller parts for the hand and gauntlet were printed and attached to the base material, for example, 90-degree guide pipe to align the string to pulley mechanism. Need for these extra parts were discovered in the assembly process of the hand's prototype. In the final product these modifications would be included in a single-piece printable model. Figure 17 shows assembled prosthesis prototype and the technical drawing are presented in appendix 3.

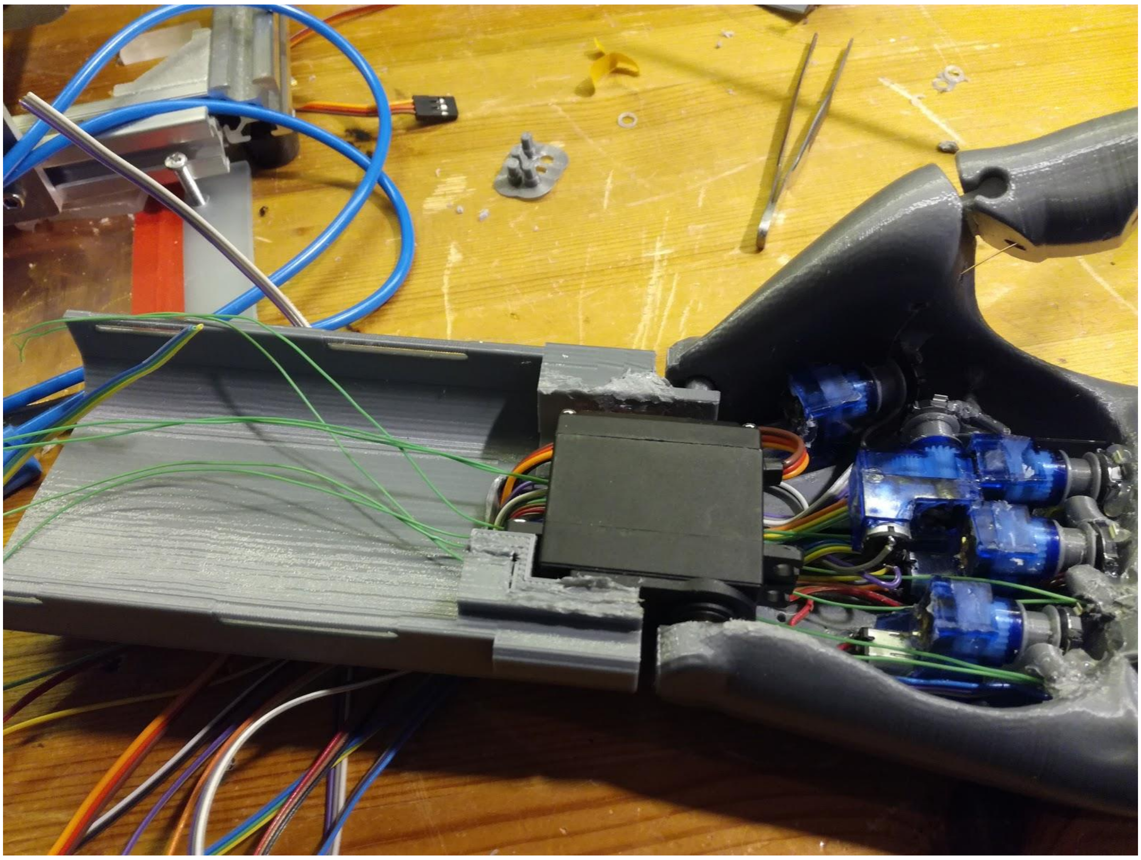


Figure 17: Completely assembled mechanical part of prosthesis.

4 Electronics Design for Prosthetic Hand

Many of modern integrated IC provides a lot of included features integrated in its package. Small number of external components needed for IC operation has benefits of lowering overall cost on electronics circuit. Furthermore, in the same time, it makes PCB design simpler and takes up a smaller footprint of PCB. Therefore, it was decided to use integrated IC's instead of designing electronics circuit form discrete components

4.1 Electronics Block Diagram.

Block diagrams are used to understand and design complete circuits by breaking them down into smaller sections or blocks. Each block performs a particular function and the block diagram shows how they are connected together. No attempt is made to show the components used within a block, only the inputs and outputs are shown. This way of looking at circuits is called the systems approach.

In the figure 18 the block diagram of the project is visible. Parts in the blue square are on the PCB circuit. These parts are electronics components that do not have mechanical functionality. Parts in the pink square are on the 3D printed hand and these components are mechanical.

EMG MyoWare sensors are created on separate PCB board and are located outside of prosthetic assembly. These sensors are connected to a main board with wires. The main reason for not integrating EMG sensors in the prosthesis gauntlet is that it is necessary to find best muscle to use for EMG signal, that could be bicep muscle or other.

There are some benefits by not integrating battery on main board PCB, such as,

- easily replaceable
- weight distribution

User has opportunity to replace battery with a spare in case of running out of charge. Also, it makes possible to swap original battery with bigger capacity batteries. Batteries are relatively heavy components, especially high capacity batteries.By providing external battery for prosthetics user can choose to have it placed somewhere else on body, for example, on bicep. This would move weight of battery away from hand itself.

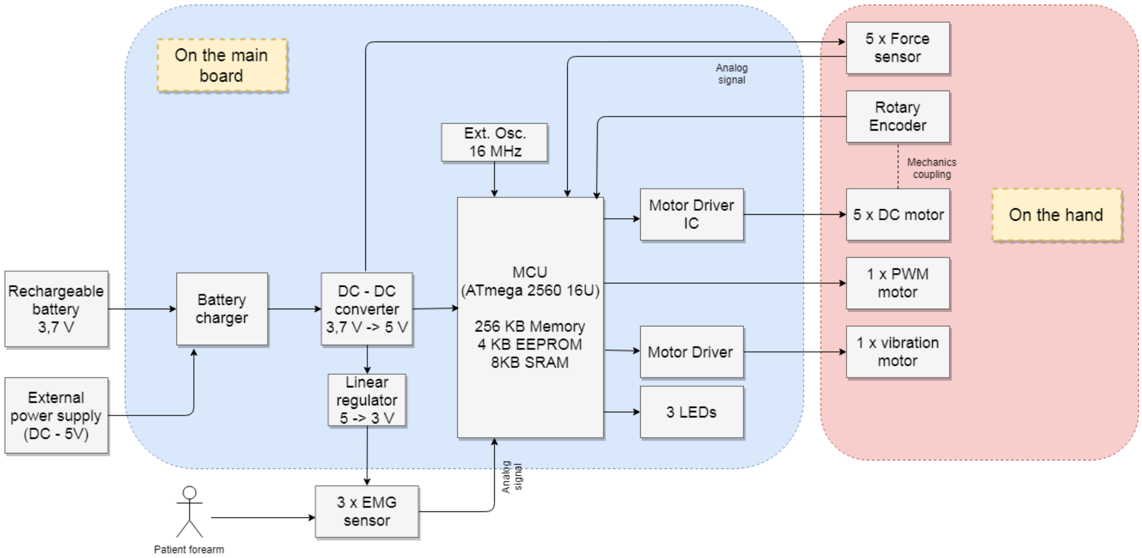


Figure 18: Electronics block diagram.

4.2 EMG Sensor Circuit

An EMG circuit consist of 3 MyoWare sensor modules and an ATmega 2560 microcontroller. Specifically designated for microcontrollers, MyoWare muscle sensor module allows very easy to be used together MCU. Figure 19 shows the connection between MyoWare sensor and MCU. The connectors J2, J3, J4, J5, are connected to microcontroller analog to digital input pins and the sensor modules are connector to the connectors via wires.

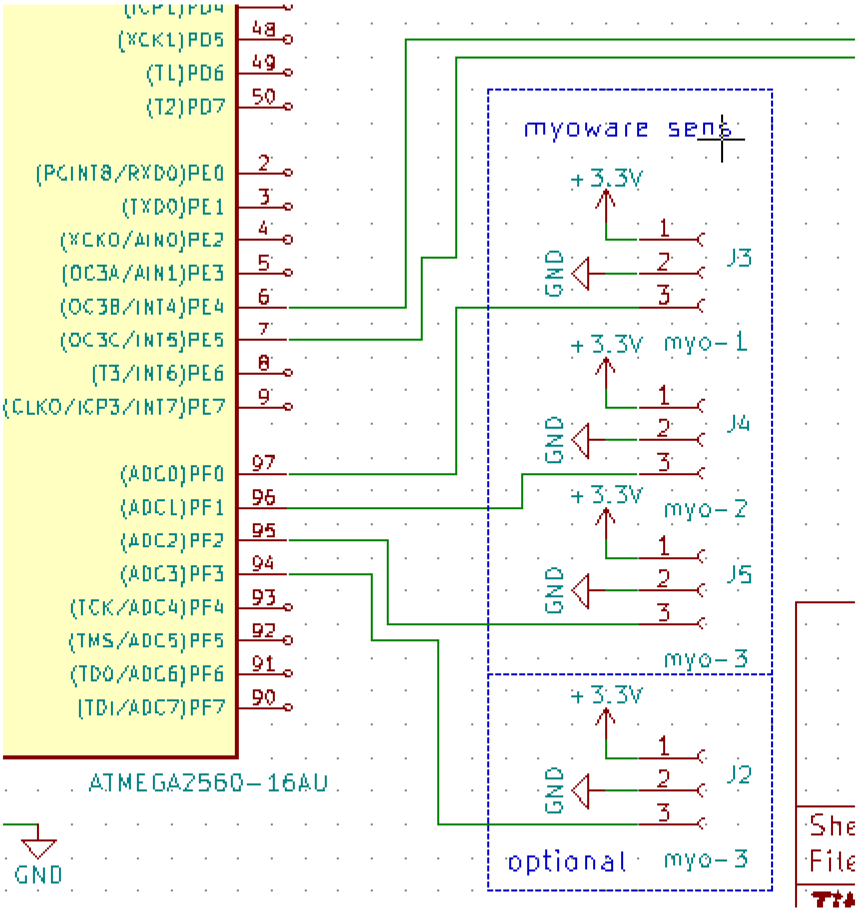


Figure 19: MyoWare sensor connection to MCU.

MyoWare sensor is a module type circuit. This sensor consists of integrated circuit and PCB board (figure 20) and biomedical sensor pads (figure 21). It has been designed as a wearable device meaning it is designed to be placed on body directly as biomedical sensor pads are attached directly to PCB board instead of using biomedical pads separately and connecting them with wires [19].

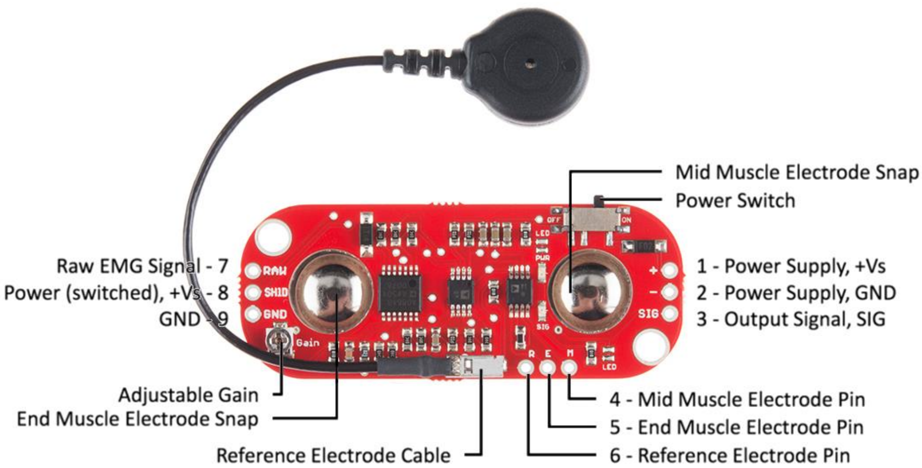


Figure 20: Sparkfun MyoWare sensor module [19].

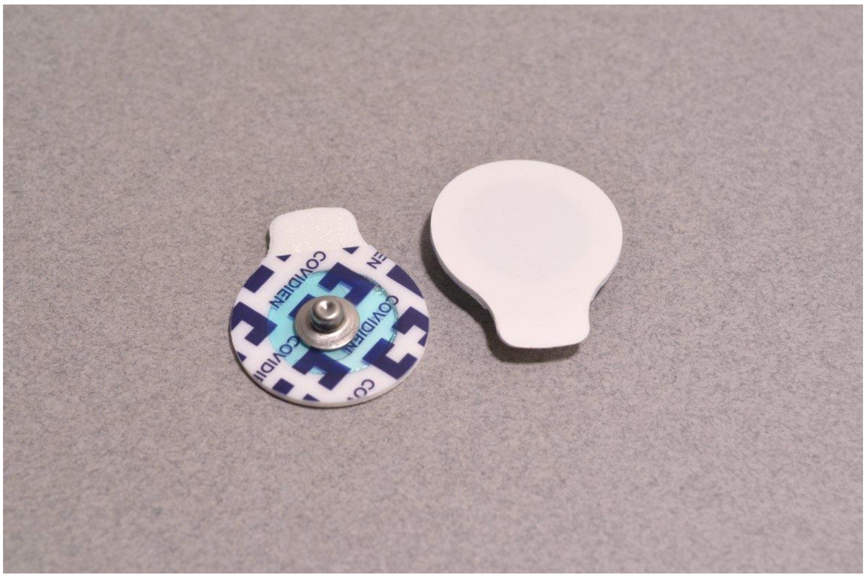


Figure 21: Biomedical sensor pads [32].

4.3 Power Source of the Device

Completed power management circuit for the device consists of four parts: power source, Li-ion battery charger, boost converter and linear regulator.

There are many battery types that are categorized in two groups

- primary cell
- secondary cell

The primary cell is battery that cannot be recharged also called alkaline battery. These batteries most commonly are in AA and AAA package. The secondary cell is rechargeable batteries. Four most common types are Lead acid, NiCd, NiMH and Li-ion. Each type has its advantages and disadvantages. In this project Li-ion Battery has been used, as it provides highest energy density over package size. In comparison NiCd and NiMH batteries with same package size has smaller capacity.

Circuit has been designed to work from minimum of single 3.7 V Li-ion battery, but it is not excluding possibility to connect multiple, of the same model, batteries in parallel connection to achieve higher capacity and longed discharge time. With minimum modification this circuit can be powered from alkaline batteries. This is explained in boost converter section under soft start function.

4.4 Battery charger circuit based on MCP73832 chip.

Li-ion charger circuit is based on MCP73832 IC. It is single cell, fully integrated Li-ion charger management controller. This integrated circuit provides many features in one single package such as small physical size, low number of external components, charging from a USB port, constant-current/constant voltage charge algorithm with selectable preconditioning and charge termination, voltage regulation is fixed with four available options: 4.20 V, 4.35 V, 4.40 V or 4.50 V, automatic power-down and thermal regulation. Differing from other Li-ion battery protection IC's these extra features are very useful as they provide safety features in this project case.

Data lines on USB micro type connector are connected with a 200-ohm resistor following dedicated charging port compliance plan [22]. In the MCP datasheet is functional block diagram of the internal circuitry for MCP73832 that explain IC working principle and different charging modes [23]. Figure 22 shows Li-ion battery charging and protection circuit.

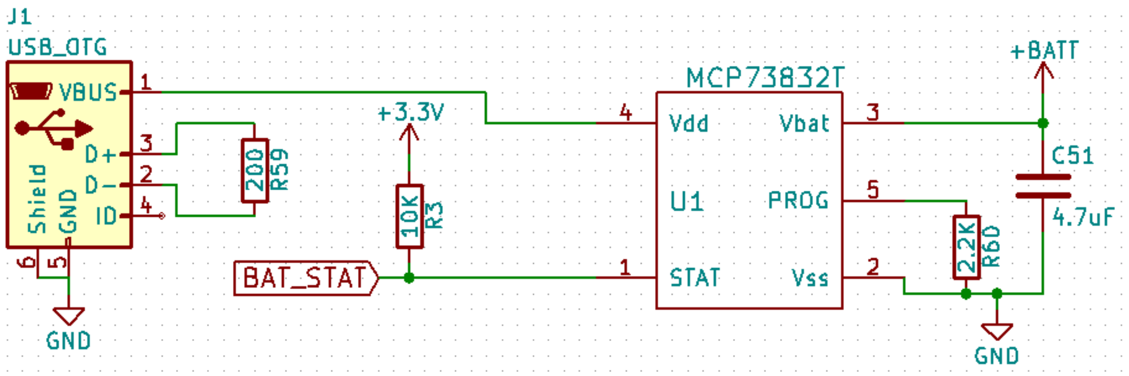


Figure 22: MCP 73832T circuit.

The charging current is set by connecting a PROG pin to Vss pin. This circuit does not provide fast charging capability of battery. The fast charge current for Lithium-Ion cells are calculated based on battery's capacity, for example, a 1000 mAh battery fast charging would be 1000 mA. Charging at this current provides the shortest charge times without degradation to the battery pack performance or life [24]. Charging with higher current would damage battery. However, the USB 2.0 standard can supply up to 500 mA of current. Newer standard has a higher current rating, but not all devices support it [25]. Therefore, to avoid drawing too much current from appliances, the charging current has been calculated to be under 500 mA. Rearranging equation 1 to calculate resistor value for setting charging current we get 2222 Ω, when charging current is chosen to be 450 mA.

$$Ireg = \frac{1000}{Rprog} \qquad (1)$$

Where: Ireg = regulated charging current, Rprog = resistance.

By closest standard value resistor of 2.2 kΩ final charging current is calculated to be 455 mA.

4.5 Boost converter

The boost converter is device whose output voltage is equal or greater than its input voltage. DC input for boost converter can be from many sources such as solar panels, fuel cells, batteries. The figure 23 illustrates basic circuit of boost converter. In this example switching element is MOSFET. Bipolar transistors also are used in switching circuitry. A choice between one or other is determined by the current, voltage, switching speed and cost.

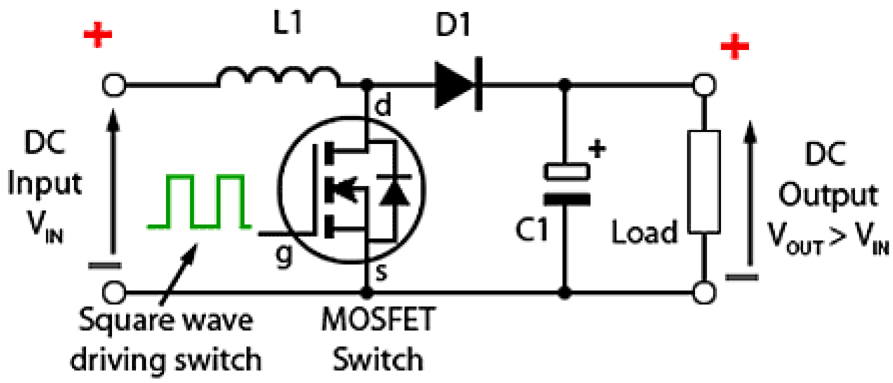


Figure 23: Basic boost converter circuit [37].

Basic boost converter operation is illustrated in figures 24, 25, 26. The figure 24 shows the circuit action in the initial state. The high-level period of the high frequency square wave is applied to the MOSFET gate at startup T=0. During this period MOSFET conducts creating short circuit at the right side of the coil L1, to the negative input terminal of the supply. Therefore, the current flows from positive terminal through coil L1 and MOSFET to negative terminal of the supply. At this moment coil is storing energy in its magnetic field. There are almost no current in rest of a circuitry as D1 and C1 has much higher impedance than the direct path of the conducting MOSFET.

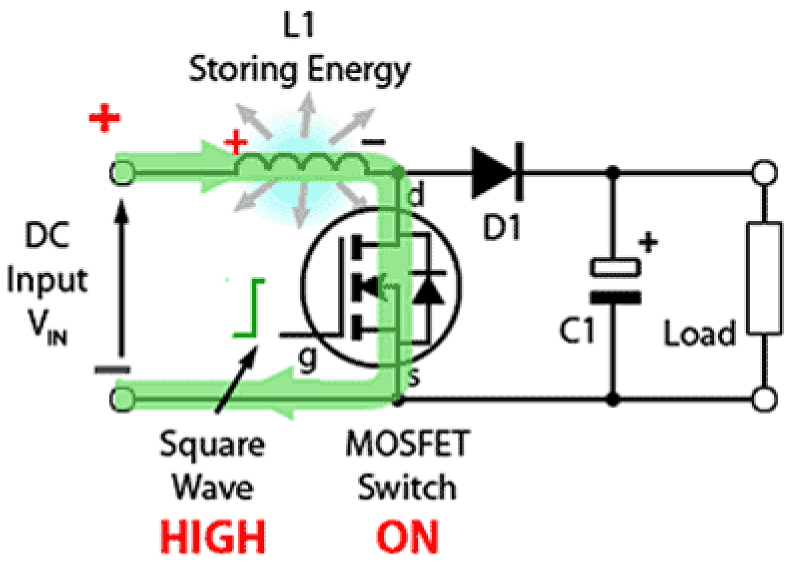


Figure 24: Circuit action in the initial state T=0 [37].

Figure 25 shows current path during time T=1. Low level period of the switching square cycle. As a MOSFET is rapidly turned off the sudden current drop is created. This causes L1 to produce back e.m.f in the opposite polarity to the voltage across L1 during the on period, to keep current flowing. This results in two voltages in series, supply voltage V_{IN} and the back e.m.f (V_L). The resulting higher voltage is V_{IN} plus V_L. There is no current path through MOSFET at this moment and current flows through forward biased diode D1 and charges capacitor C1 to V_{IN} plus V_L voltage, minus voltage drop in D1 and supplies the load.

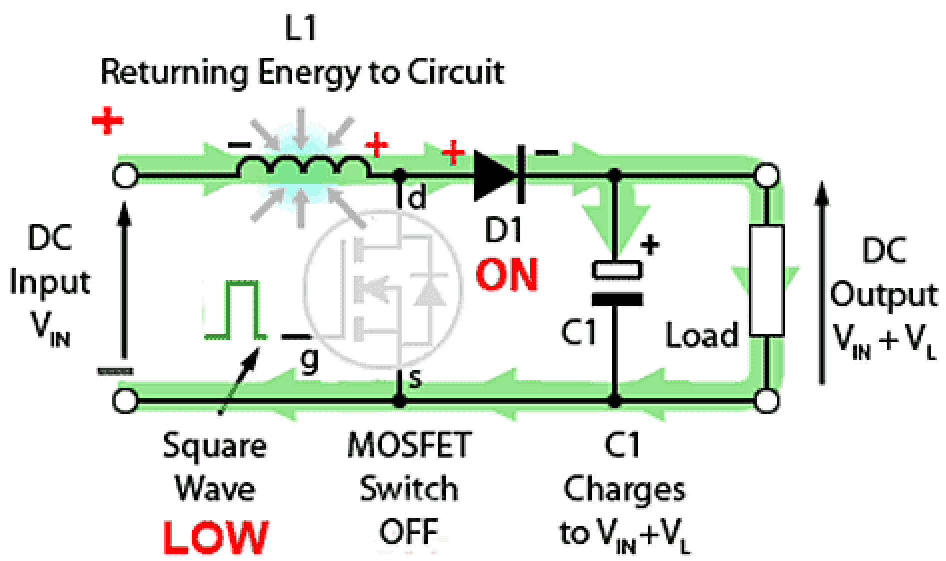


Figure 25: Circuit action in the switch off state T=1 [37].

Figure 26 shows the circuit action during MOSFET on period T=2, after initial startup period T=0. Every time MOSFET is conducting the cathode of the diode D1 is more positive than its anode, this happens due to charge in C1. D1 is turned off so that the output and input are isolated from each other. However, load is still supplied with V_{IN} plus V_L charged capacitor. Even this drains charge of C1 though load in this period, the C1 is recharged each time the MOSFET is turned off. This maintains almost steady supply to load.

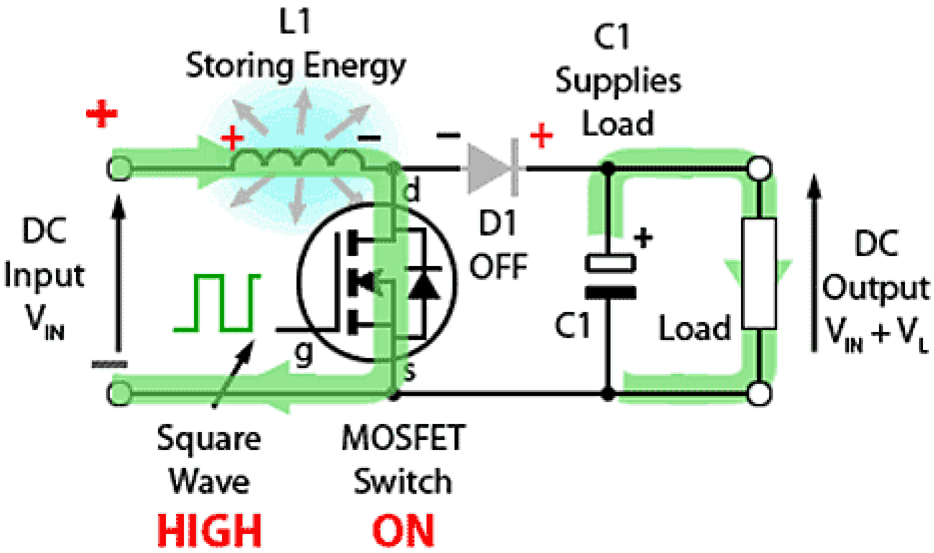


Figure 26: Circuit action in the switch on state T=2 [37].

The boost converter circuit for the project is designed based on LT1308 IC. The LT1308 is a fixed frequency step-up DC/DC converter that operates over a 1 V to 10 V input voltage range, starts into heavy loads, lower quiescent current in shutdown: 1 µA and low-battery detector.

The LT1308 combines a current mode, fixed frequency PWM architecture with burst mode. Micropower operation to maintain high efficiency at light loads. The operation can be best understood by referring to the datasheet.

The figure 27 shows the circuit designed for this project. Output voltage is set by using a resistor divider to FB pin of IC. Low battery indicator has also been set by a voltage divider that is connected to a LBI pin that is connected to the internal reference. When the LBI voltage is above internal reference voltage, the LBO will be pulled to a 0 V level, and when the LBI voltage drops below reference, the LBO will be pulled to a circuit output voltage that is read by the MCU.

Soft start function is intended when using a LT1308 with alkaline cells. In some cases when it may be undesirable for the LT1308A/ LT1308B to operate at current limit during start-up, e.g., when operating from a battery composed of alkaline cells. The inrush current may cause sufficiency internal voltage drop to trigger a low-battery indicator. A programmable soft-start can be implemented with 4 discrete components. In the figure 27 these components are indicated R6, R4, C2 and Q3. PCB design has been made with possibility to include soft start function by soldering these components to the footprints on the PCB.

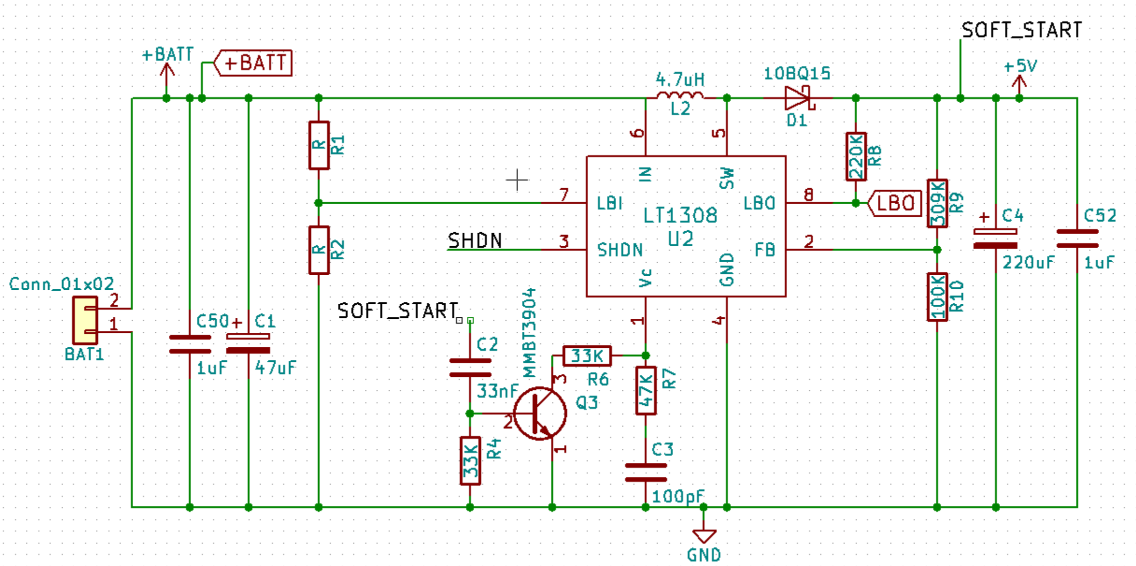


Figure 27: Boost converter circuit based on LT1308.

Output Voltage is calculated by using equation 2. To achieve 5 V output voltage, R10 is chosen to be 100 kΩ using these values and rearranging equation R9 is calculated to be 309836 Ω. Finally choosing standard value of resistor R9 to 309 kΩ the final output voltage is 4.99 V.

$$Vout = 1.22\left(1 + \frac{R1}{R2}\right) \qquad (2)$$

Low battery indicator (LBI) is calculated by using equation 3. This formula is valid when R2 is 100 kΩ as it is stated in the LT1308 datasheet [32]. The VBI was chosen to use 2.8 V for low battery indication. This results in R9 value to be 1.3 MΩ.

$$R1 = \frac{VBI - 0.2}{2 * 10^{6}} \qquad (3)$$

4.6 Linear regulator

A linear regulator is a system used to maintain a steady voltage. Regulator resistance varies according to the load and results in a constant output voltage. This regulating device acts like a variable resistor and continuously adjusts the voltage divider network in order to maintain an output voltage which is constant. The difference between the input voltage and regulated voltage is continually dissipating as waste heat [27]. MyoWare sensor can operate from 2.9 V to 5.7 V supply. Therefore, 5 V power supply from boost converter would be suitable for powering MyoWare sensor. However, there are two reasons not to use 5 V supply from boost converter. The first reason is that the signal from MyoWare sensor is very sensitive to noise and second reason is that the boost converters by their characteristics introduces more noise to the system than linear regulators. Furthermore, since the boost converter also supplies the power for the rest of the circuit, the noise from the other components will interfere the EMG sensors signal if they use the same power source. For all above reasons, powering MyoWare sensors from the output of the linear regulator is a good choice to eliminate the inherent noise as much as possible.

The linear regulator to power MyoWare sensor is AP7330. It is a low dropout linear regulator with high output voltage accuracy, low RDS(ON), high PSRR, low output noise and low quiescent current. Output Current: 300 mA, VOUT Accuracy ±1%, Low VIN and wide VIN Range: 1.8 V to 5.5 V and wide VOUT Range: 1.0 V to 4.5 V. Figure 28 shows the designed circuit based on AP7330 IC

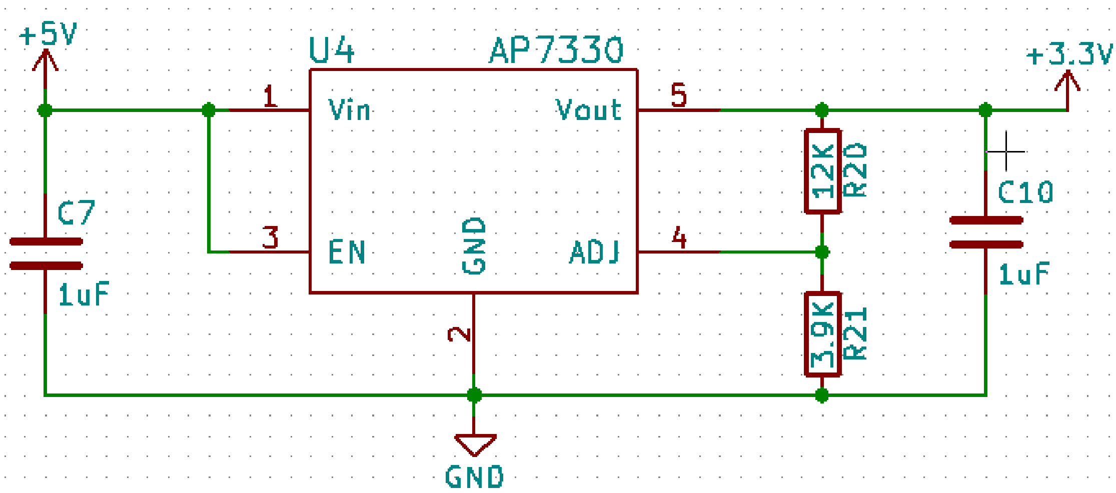


Figure 28: Designed circuit based on AP7330 IC.

Output voltage was set to be 3.3 V as it is common voltage for MCU operation. This is important due to MyoWare sensor will amplify signal to its supply voltage. And this voltage level is still in safe limits of MCU analog pin input voltage. The output voltage of the regulator is calculated using equation 4.

$$Vout = Vref\left(1 + \left(\frac{R1}{R2}\right)\right) \quad (4)$$

V_{ref} is an internal reference voltage 0.8 V. To maintain the stability of the internal reference voltage, R2 needs to be kept smaller than 10 kΩ [34]. R21 was chosen to be 3.9 kΩ, in equation 4 it is R2. By rearranging equation, the R20 and final output voltage is calculated. R20 is 12185 Ω and standard value of 12 kΩ resistor is chosen. Finally output voltage is calculated to be 3.26 V.

4.7 Motor control circuit.

During modification of the finger actuator motor their control circuity was replaced with H bridge motor driver IC. In general, an H-bridge is a simple circuit, containing four switching elements, with the load at the center, in a H-like configuration. Figure 29 shows the H bridge circuit, the load in middle in this case motor and four switching MOSFETS Q1, Q2, Q3, Q4 as switches.

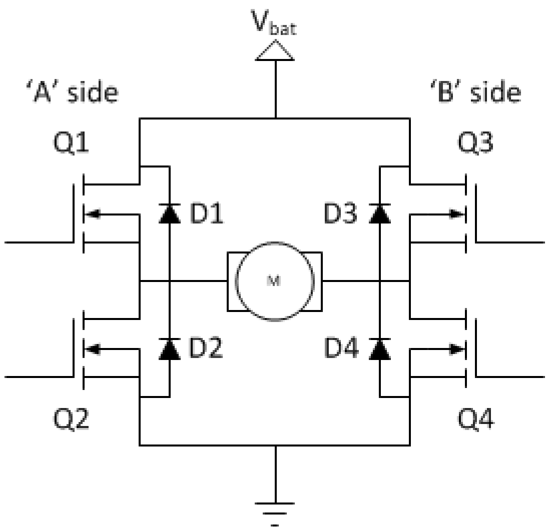


Figure 29: H bridge circuit model [28].

Figures 30 and figure 31 illustrate the examples of clockwise and counterclockwise direction control of the motor. The rotation in clockwise direction is demonstrated by turning on Q1 and Q4, the left lead of the motor will be connected to the power supply, while the right lead is connected to ground. Current starts flowing through the motor which energizes the motor in this example the forward direction and the motor shaft starts spinning.

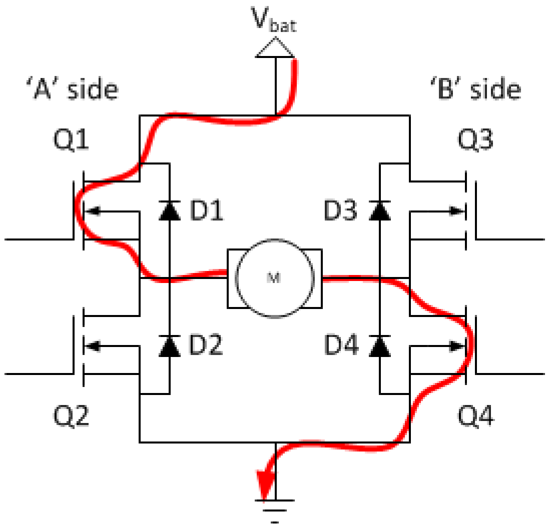


Figure 30: H bridge rotation clockwise direction example [28].

On the other hand, if Q2 and Q3 are turned on, the reverse will happen. The left lead of the motor will be connected to the ground, while the right lead is connected to power supply. The motor gets energized in the reverse direction, and the shaft will start spinning backwards. This demonstrated in the figure 31.

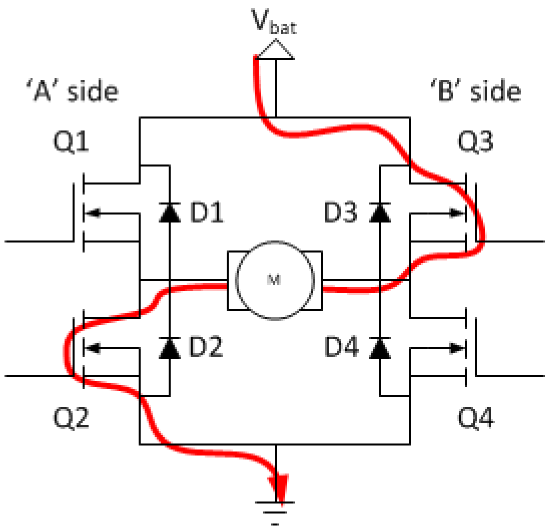


Figure 31: H bridge rotation counterclockwise direction example [28].

The Q1 and Q2 should never be on at the same time. This creates short circuit that destroys switching elements. Same is applied to Q3 and Q4.

The motor control circuit is designed by using ZXBM5210 H bridge IC. The integrated full bridge driver output stage is designed to minimize audible switching noise and electromagnetic interference (EMI) providing a low noise solution, internal over current protection, under voltage lockout and over voltage protection, over temperature protection, four modes of operations: Forward, Reverse, Brake and Standby and 6 kV ESD withstand capability [29]. The designed circuit based on ZXBM5210 IC is shown in the figure 32.

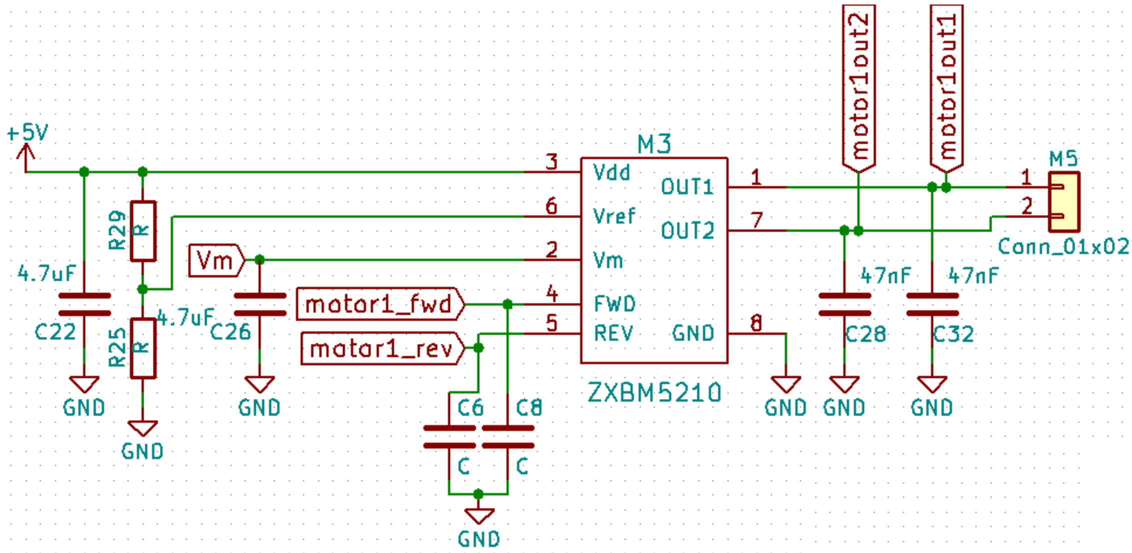


Figure 32: Finger actuator motor control circuit.

4.8 Touch sensor and feedback loop circuit

A force sensitive resistor is a type of variable resistor whose resistance decreases when the applied force increases. Force sensitive resistors are also known as force sensing resistors (FSR), force sensor, or pressure sensor [30]. Touch sensor working princple is based on a simple resistor divider, where one resistor is a fixed value and other resistor is changing its resistance based on pressure. In the figure 33 is visible actual sensor image. The black round part is actual sensing area. Figure 34 shows an actual circuit of forces sensor where fixed value resistor is marked R34 and actual sensor is connected to connector via wires.

Figure 33: Force sensors.

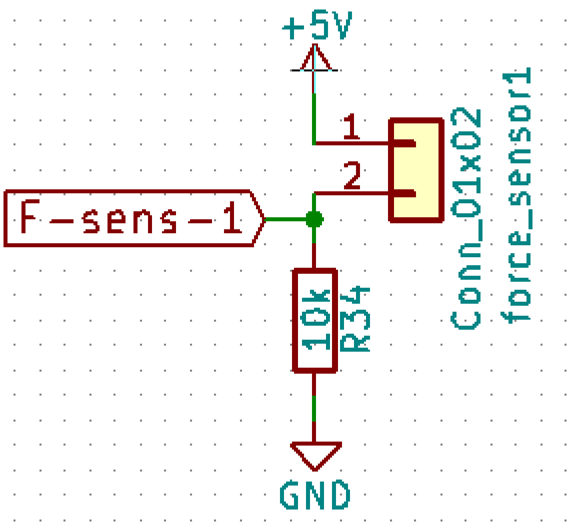


Figure 34: Force sensor circuit.

The figure 35 shows a segment of a MCU circuit where force sensor signals are fed in to analog pins of a microcontroller. It also shows battery voltage signal +BATT.

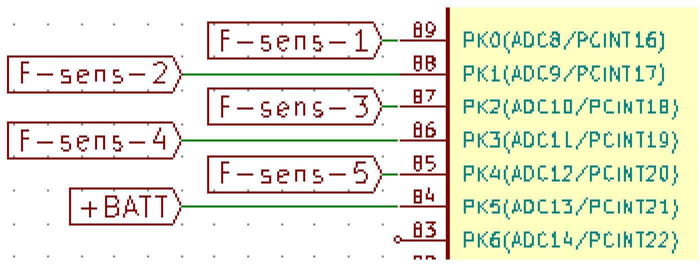


Figure 35: Force sensor connections to MCU

4.9 Microcontroller circuitry

The chosen microcontroller for this project is a ATMEGA 2560. Circuit has been designed by following recommendation of a ATMEGA 2560 datasheet. Figure 36 shows part of the MCU circuit where a reset switch, external clock oscillator. External oscillator sets the clock frequency of the MCU and 16 MHz is a maximum stable clock frequency supported by a ATMEGA 2560 microcontroller. Therefore, 16MHz crystal oscillator was chosen. Reset pin is connected to supply voltage through 10 kΩ pull-up resistor, this pulls pin to 5 V level during normal operation. When reset switch is pressed, the switch creates short circuit from Reset pin to 0 V level, which puts MCU into reset mode.

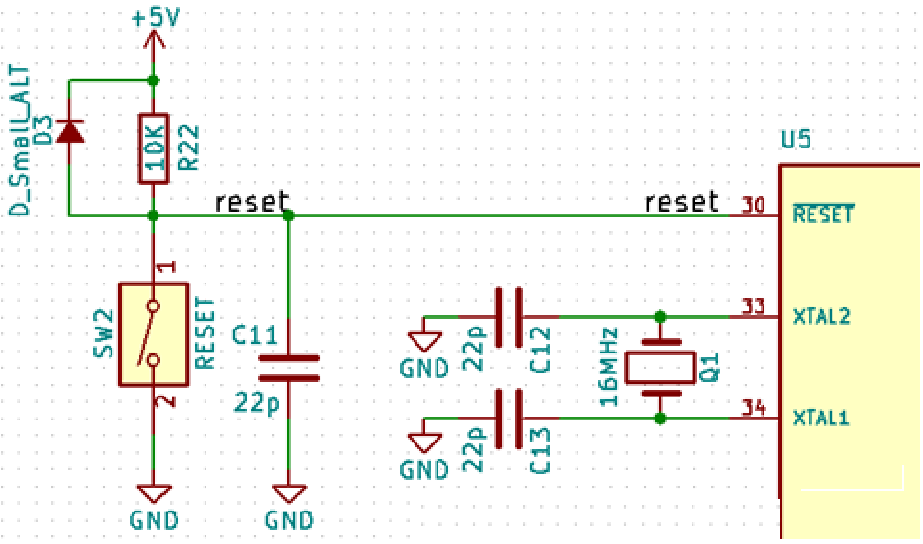


Figure 36: MCU reset and external oscillator connections.

Figure 37 shows the bypass capacitor connections to MCU. These capacitors are used to filter AC noise in the DC supply voltage, and are highly recommended in MCU datasheet to ensure stable operation of microcontroller. The Bypass capacitors are applied between the power supply pins VCC and GND of integrated circuits. On PCB they are physically located as close as possible to these pins. They also provide immediate current demands of an integrated circuit whenever it switches on.

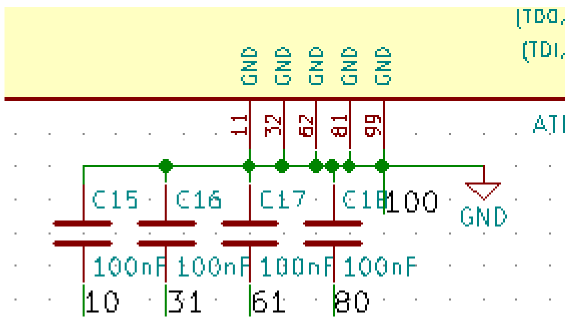


Figure 37: Bypass capacitor connections.

The figure 38 shows the other signals connections. The signal connection follows two main principles. First being a signal types, the digital signals are connected to digital pin of MCU and analog signals are connected to analog pins. Second principle is ease of

PCB design by taking in account physical pin location and other circuitry locations to each other to make PCB design less complicated.

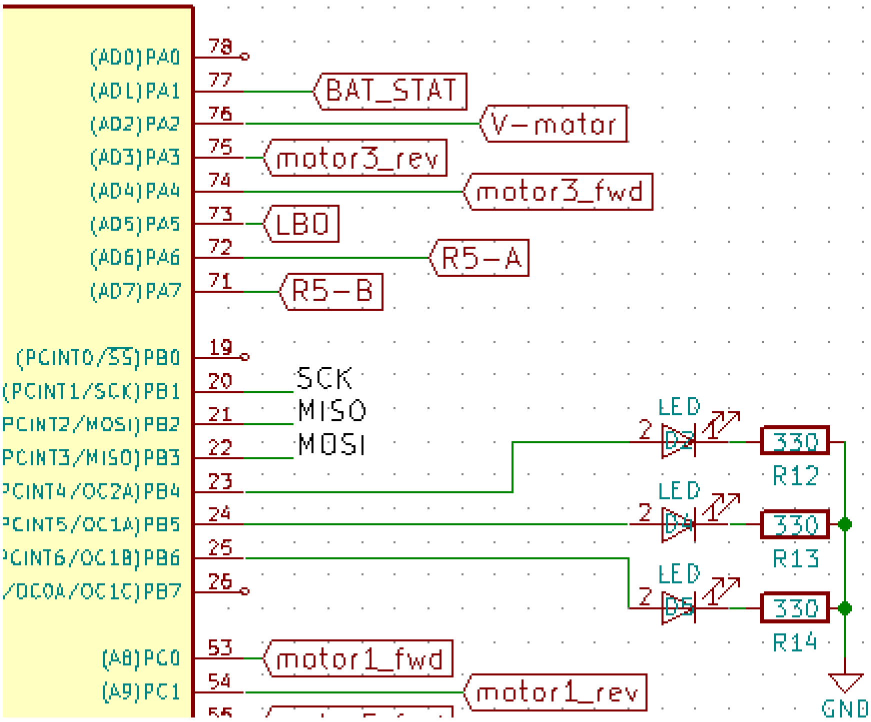


Figure 38: The signal connections

The full schematic of the circuit is presented in the appendix 1.

5 PCB design:

A printed circuit board, mechanically supports and electrically connects electronic components using conductive tracks, pads and other features etched from one or more sheet layers of copper laminated onto and/or between sheet layers of a non-conductive substrate. Components are generally soldered onto the PCB to both electrically connected and mechanically fasten them to it.

Prosthesis PCB specification:

- size 111.3 mm x 41.2 mm
- four layers
- thickness 1.6 mm
- solder mask Green
- material FR4-standard Tg 140C

Due to the high component count and layout density, the PCB has been designed on a four-layer board. Furthermore, a four-layer board design provides a couple of notable feature. Top and bottom layers are used for signal traces, while internal two layers are usually power and GND layer on four-layer board. This makes PCB design simpler and can help to reduce physical size of it. When designing PCB, it is recommended to follow the integrated circuit manufacturer PCB design guidelines, if such an information is provided. Manufacturers of IC have validated these guidelines to ensure optimal functionality and stability of the circuit. This information is common in audio circuits and switching power regulators datasheets. Switching power supply circuits usually utilize high switching frequencies. A poorly designed PCB, can create parts of circuit to act as an antenna. This would generate unwanted noise. In some case that could even introduce instability in circuit. In the figure 39 is a segment of PCB layout guide form LT1308 boost converter datasheet.

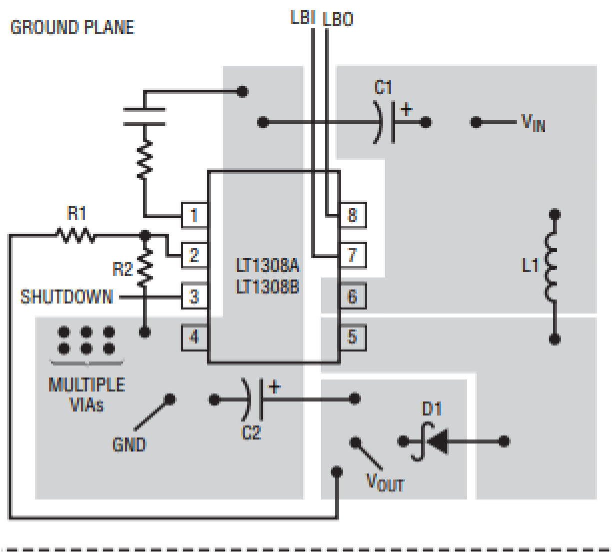


Figure 39: datasheet example [33].

As it has been mentioned in the ‘Soft start design’ section of this document, it is possible to power this circuit from alkaline batteries. In the figure 40, previously mentioned components are marked with bright yellow outline border. These components are not physically present on an assembled board. However, including these components in the PCB layout ensure possibility to utilize such functionality without designing new PCB board. Note that it is not always possible to include extra components if the space on the PCB is limited. Figure 41 shows assembled PCB that is ready to be installed in hand’s gauntlet.

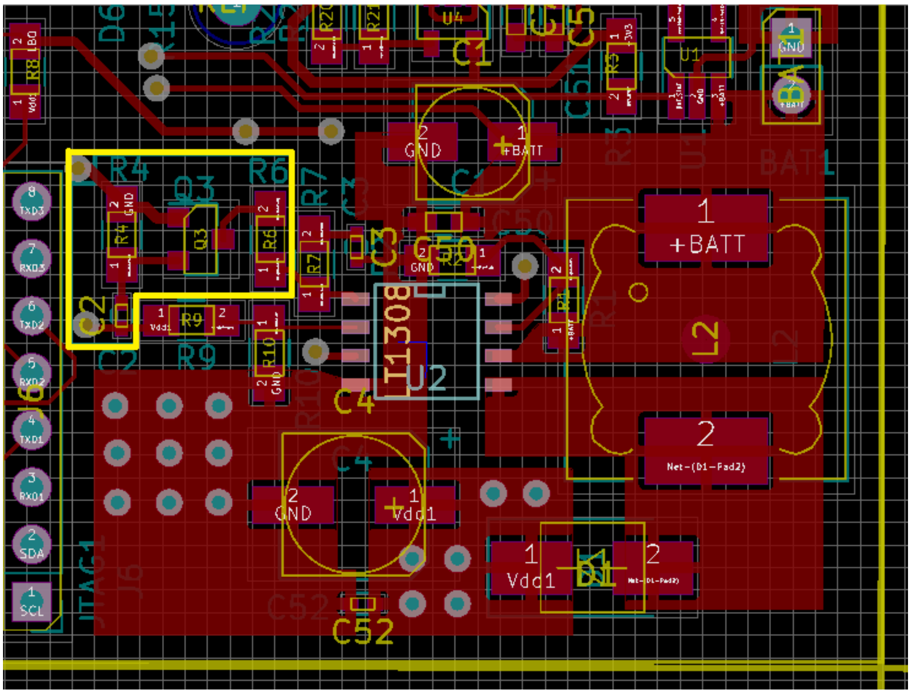


Figure 40: designed PCB board section

Figure 41: Assembled PCB.

6 Hand gestures and control.

The hand is controlled by EMG signals. These signals are read by MyoWare sensor placed on surface of the skin above muscle to be read. For best signal quality the sensor needs to be placed above muscle correctly. The figure 42 shows different placement position of the sensor above bicep muscle and the effect on signal.

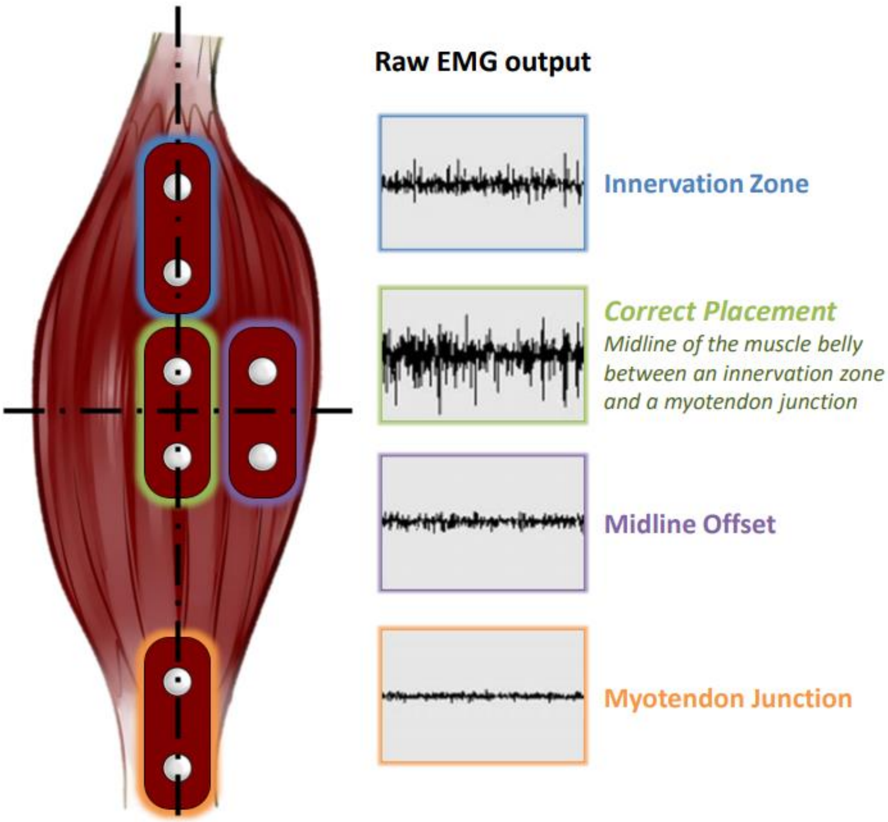


Figure 42: EMG sensor output dependence of placement [12].

There are total of three EMG sensors placed on patient upper hand. Figure 43 show all placed sensors on the hand. The sensor 1 is placed on flexor digitorum muscle, sensor 2 is placed on extensor digitorum muscle and sensor 3 is placed on short head bicep muscle [38].

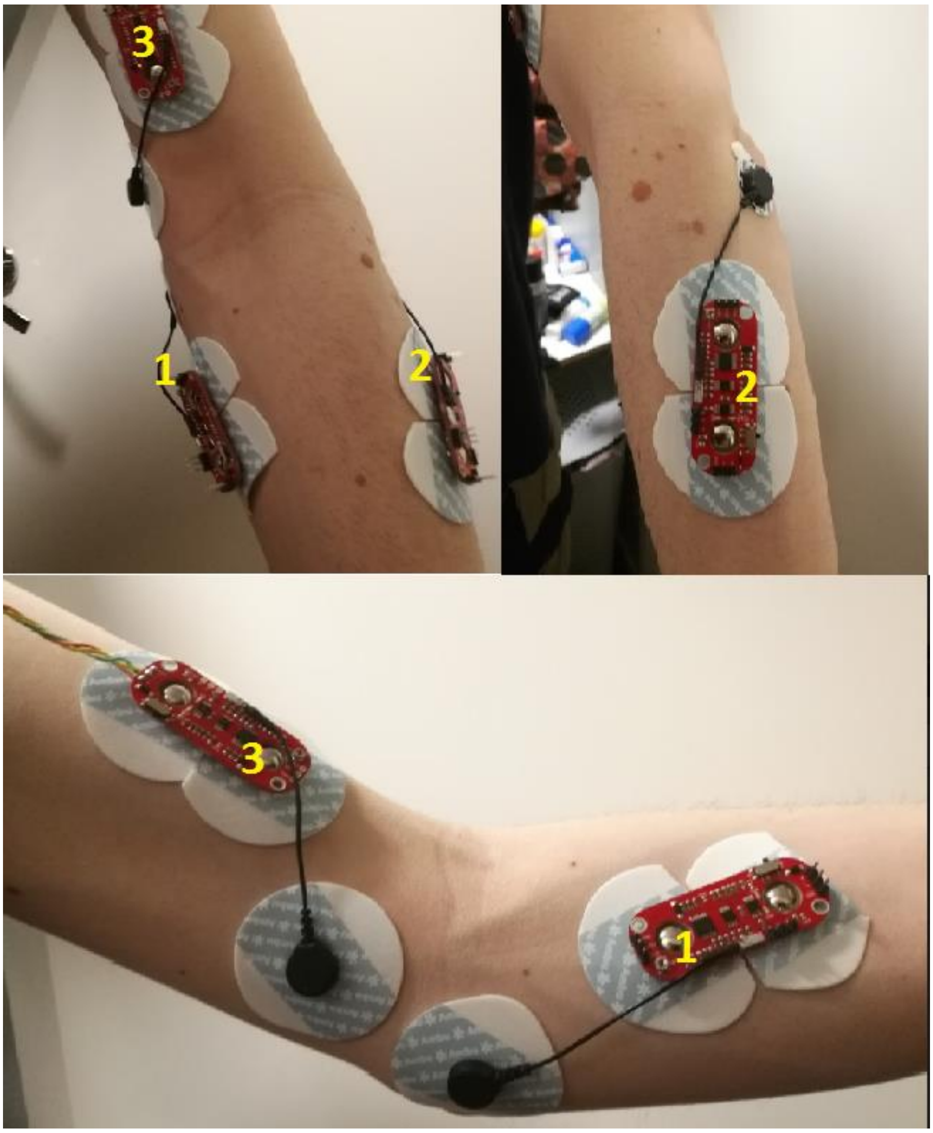


Figure 43: EMG sensor placement.

The EMG signal from muscle is very weak, this signal needs to be amplified, rectified and integrated. The MyoWare sensor module is designed for this purpose. This signal then is passed to MCU analog to digital converter pins where further analysis can be done. In the figure 44 the signal processing made by MyoWare sensor is shown [38].

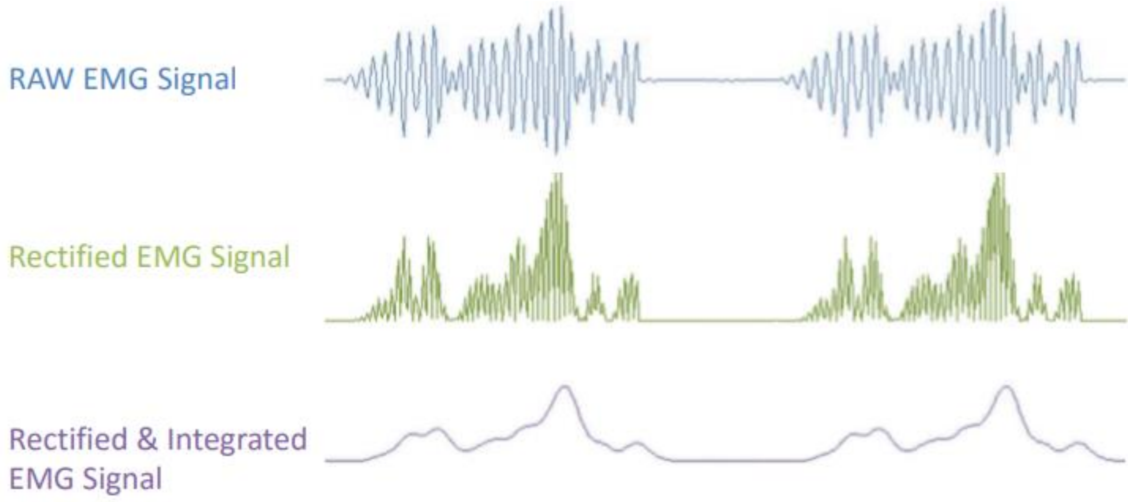


Figure 41:EMG signal processing by MyoWare sensor module.

The healthy human hand can perform many complicated gestures thank to complex bone and muscle structure. However, the created prosthetic hand in this project is capable of six gestures. These gestures are programed in the hand's MCU.

For the patient to use prosthetic hand it is necessary to calibrate it. The calibration is done by selecting calibration mode. Where device is reading data of relax muscle and six different hand gestures. This records data generated by muscle activity form each gesture. After calibration user selects operation mode. When user makes one of six previously recorded gestures the hand will respond accordingly. The figure 45 shows the real hand gestures and corresponding prosthesis hand gesture. For more detailed explanation of software and signal analysis refer to Ngoc Tiep Nhu Nguyen work [38]

No.	The Real Hand Pose	Description	The Prosthetic Hand Pose	Description
1.	 Fist	All five fingers close	 Fist	All five fingers close
2	 Fist and wrist flexion	All five fingers close and wrist flexion	 Point	All four fingers close except index finger
3	 Wrist flexion	Wrist flexion	 Rock	All three fingers close except index and pinky fingers
4	 Wrist extension	Wrist extension	 Pinch	All three fingers close except ring and pinky fingers
5	 Rest	All five fingers open	 Rest	All five fingers open
6	 Bicep	Bicep muscle tightens	 Wrist flexion	Wrist move up to 50 degree from rest position.

Figure 45: Table of programed gesture depending on user hand muscle activity [38].

7 Cost analysis of the Prosthetic hand.

The one of project targets was to create affordable prosthetic hand for patients in developing counties. The hand developed in the project is still in prototype stage. Therefore, a cost analysis is necessary to estimate future expenses and price per unit of the prosthetic hand. Current cost of one unit is 189.06 Euro and the cost breakdown is listed in table 1. The current hand prototype is using three MyoWare sensors, which is 48.5% of the total cost. It is also the most expensive component in the hand at 30.53 Euro per sensor. To lower cost for prosthetic hand it is possible to reduce amount of EMG sensors from three to two. However, to maintain same functionality as with three sensors, more advanced signal processing algorithm development is necessary. Contradictory to lowering cost at prototype stage the cost will increase. This is due to the need to create proper socket for stump and need to improve accuracy of some electromechanical components that cost more. Even though the 3D printing new gauntlet would not increase price significantly the need for lining for it would. With the current estimate of price per lining together with a change of some components also keeping all three EMG sensor the price per unit would be approximate 250 Euros. In comparison with current commercially available myoelectric prosthetics that my cost almost 80000 Euro, the goal of creating low cost prosthetic hand has been achieved.

Table 1: The device cost by part

Description	Vendor	Cost/Unit (€)	Quantity	Total cost (€)
PCB board		8.4	1	8.4
MyoWare Muscle sensor	Mouser	30.53	3	91.59
Force sensor	Mouser	5.532	5	27.66
LT1308BCS8	Mouser	5.4	1	5.4
SG90 motor	Aliexpress	1.34	5	6.7
MG996R big servo motor	Aliexpress	4.08	1	4.08
MCP73832	Mouser	0.48	1	0.48
ATMega 2560 16AU	Mouser	10.3	1	10.3
ZXBM5210 Motor driver	Mouser	0.81	5	4.05

P15965CT-ND Rotary encoder	Mouser	1.48	5	7.4
Resistor	Mouser	0.01	30	0.3
Capacitor	Mouser	0.01	20	0.2
Filament	Clas Ohlson	25	0.3	7.5
Other	Mouser	N/A	N/A	15
			Total	189.06

8 Conclusions

The main goals of the project were to create low cost prosthesis hand controlled by EMG signal from upper arm muscles. All goals have been achieved with different successes. The hand control using EMG signals has not been tested with real patient which has lost its hand, but only with healthy individual. There is no collected data from real patient forearm and it is not possible to tell if muscle activity is enough for the sensor to detect the muscle activity. With better successes feedback signals and low cost has been achieved. The visual feedback is provided by LED’s, the device has three LED’s that can be induvial programed to provide user with information. In the prototype the blue LED is used to display low battery warning and the other two show different stages of the device calibration. Haptic feedback is achieved with small vibrating motor, that can be programed to provide different information to user, like the mobile phone. Although not everyone can afford 3D printer the technology is widely available at low cost or in some cases with no cost at all. For some examples, many educational institutions, hacker spaces and charity organizations have 3D printer available for use free of charge or by paying only for used amount of the printing filament.

The main shortcoming of the current device is that it cannot be scaled. The current construction of the device only supports one size and not everyone will able to use it. The hand is modeled for adult person hand size and not for kid’s size. The other shortcomings could be considered the weight of hand. Total weight is 412 grams including batterie and all three EMG sensors and hand by itself weight is 348 grams. Also devise requires calibration which makes use of the devise more complicated. Therefore, by considering previously mentioned shortcoming several improvements are possible for the next model. The better material choice would one of the improvements. The material for printed parts of the hand is a LPA plastic. A PLA is not the lightest printing material available on the market. There are different materials available for 3D printing that is much lighter, for example, filaments with carbon fiber additives offer up to 20% weight saving. It is also possible to experiment with internal filling density and structure of the hand to lower the weight. The second shortcoming that can be improved is mechanics. Currently to assemble hand it is necessary to modify many components, such as motors and palm itself. The hand should be designed so that there is no extra modification needed on parts and modules. In addition, some parts should be embedded in the 3D printed model itself and place for components allocated.

From the electronics point of view there are also several improvements needed. Firstly, the rotary encoded feedback is only providing rotation information and speed, but is not providing position of the fingers. This can be solved by replacing incremental encoder with an absolute type encoder or by using limit switches for homing and calibration. Secondly, the wires should be replacing with ribbon cable or flat flex PCB. The connectors on the PCB board should be replaced with a single connector instead of many connectors distributed across PCB. Finally, the PCB board can be made almost in half of size. It can be achieved by designing component placement on both sides, this would also decrease price of PCB manufacturing.Even though the project still needs improvements the overall project can be considered successful.

References

[1] Paul Xue Bang Hu. Published 1997 “Development of A Pediatric Prosthetic Hand with A Two-Degree-of-Freedom Thumb” accessed 11.04.2018 < https://tspace.library.utoronto.ca/bitstream/1807/11710/1/MQ28865.pdf >

[2] M. Moreo. Published 25 Nov 2016 “Parametric design of a 3D printable hand prosthesis for children in developing countries” accessed 10.04.2018 < https://pdfs.semanticscholar.org/3492/466936e797a0a834f094cc01cb3f607425c7.pdf >

[3] Bill Geiger. Published 2017 Aug 17 “How to Build Monster Forearms” Accessed 5.12.2018 < https://www.bodybuilding.com/fun/how-to-build-monster-forearms.html >

[4] Published 2018 Apr 28 “Prosthesis” accessed 5.04.2018 <https://en.wikipedia.org/wiki/Prosthesis#Myoelectric>

[5] Published 2018 Apr 28 “Prosthesis” accessed 5.04.2018 < https://en.wikipedia.org/wiki/Prosthesis>

[6] accessed 15.03.2018 <http://www.chabloz-orthopedie.com/en/orthopedics/Upper-limbs/2/Cosmetics-prostheses/12/page/Different-kinds-of-attachment-sockets/88>

[7] Elsevier, LTD. Published 2013 “Applied anatomy of the wrist, thumb and hand” accesed 13.03.2018 <http://www.orthopaedicmedicineonline.com/downloads/pdf/B9780702031458000727_web.pdf>

[8] Amioy Kumar, Tanvir Singh Mundra and Ajay Kumar. “Hand Anatomy” accessed 12.03.208 <https://pdfs.semanticscholar.org/e620/737dd7c7183d1e6efa36e62e92a15683948e.pdf>

[9] Piper, H. Published 2018” Elektrophysiologie menschlicher Muskeln” accessed 5.03.2018 <https://en.wikipedia.org/wiki/Electromyography>

[10] M.B.i. Raez, M.S. Hussain, F.Mohd-Yasin. Published 23 Mar 2006 “Techniques of EMG signal analysis: detection, processing, classification and applications <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1455479/>

[11] https://www.delucafoundation.org/download/bibliography/de-luca/books_muscles-alive-03.pdf

[12] Sparkfun.” MyoWare Muscle Sensor Kit” accessed 1.04.2018 <https://learn.sparkfun.com/tutorials/MyoWare-muscle-sensor-kit>

[13] Gyrobot. Published 3Jul 2014 ”Flexy-Hand2” accsessed 25.02.2018 <https://www.thingiverse.com/thing:380665>

[14] Sean Rohringer Published 20 Feb 2018 “3D printed Filament Guide 2018 -The Top 25 Types” accessed 6.03.2018 <https://all3dp.com/1/3d-printer-filament-types-3d-printing-3d-filament/>

[15] “Evrything You Need To Know About Polylactic Acid (PLA)” accessed 7.03.208 <https://www.creativemechanisms.com/blog/learn-about-polylactic-acid-pla-prototypes>

[16] https://www.velleman.eu/products/view/?id=432808

[17] http://www.ee.ic.ac.uk/pcheung/teaching/DE1_EE/stores/sg90_datasheet.pdf

[19] https://www.sparkfun.com/products/13723

[20] http://depts.washington.edu/matseed/batteries/MSE/classification.html

[21] http://batteryuniversity.com/learn/article/secondary_batteries

[22] USB Implementers Forum Inc. Published 2011 Oct 26 “USB Battery Charging1.2 Compliance Plan Revision 1.0” accessed 7.05.2018 <http://www.usb.org/developers/docs/devclass_docs/USB_Battery_Charging_1.2.pdf>

[23] Microchip. “Miniature Single-Cell, Fully Integrated Li-Ion, Li-Polymer Charge Management Controllers” accessed 7.05.2018 <http://ww1.microchip.com/downloads/en/DeviceDoc/20001984g.pdf>

[25] https://www.extremetech.com/computing/115251-how-usb-charging-works-or-how-to-avoid-blowing-up-your-smartphone

[26] http://ethesis.nitrkl.ac.in/4811/1/109EE0612.pdf

[27] http://www.futureelectronics.com/en/regulators-references/linear-regulators.aspx

[28] Andras Tantos. Published online 2011 “H-bridge control” accessed 6.05.2018 < http://www.modularcircuits.com/blog/articles/h-bridge-secrets/h-bridge-control/ >

[29] https://www.diodes.com/assets/Datasheets/ZXBM5210.pdf

[30] http://www.physics-and-radio-electronics.com/electronic-devices-and-circuits/passive-components/resistors/forcesensitiveresistor.html

[31] https://www.digikey.com/product-detail/en/panasonic-electronic-components/EVQ-VVD00203B/P15965CT-ND/3873471

[32] https://www.bc-robotics.com/shop/biomedical-sensor-pad-10-pack/

[33] Linear Technology. “High Current, Micropower Single Cell, 600 kHz DC/DC Converters” accessed 7.05.2018 <http://www.analog.com/media/en/technical-documentation/data-sheets/1308abfb.pdf?domain=www.linear.com>

[34] https://www.diodes.com/assets/Datasheets/AP7330.pdf

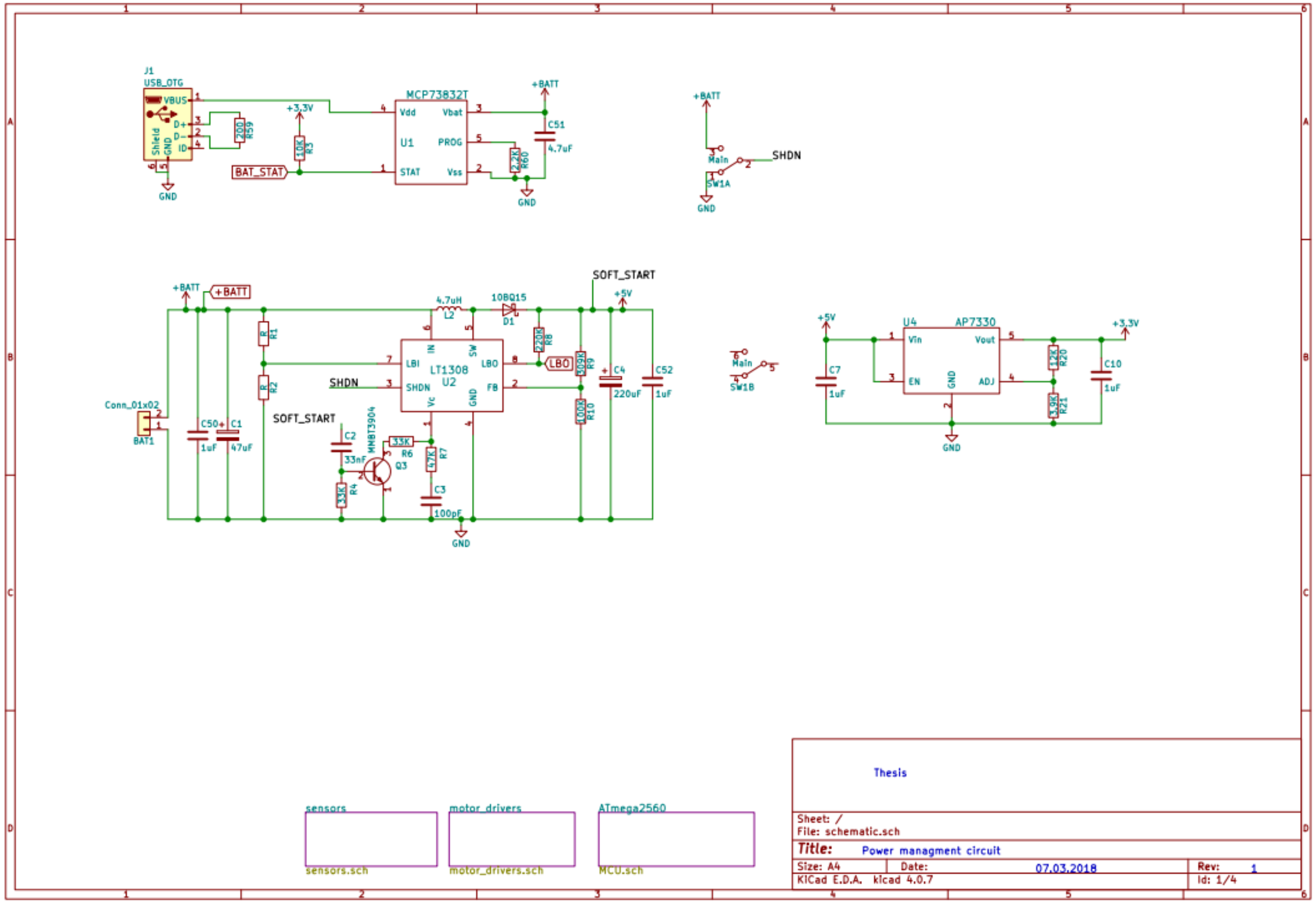
[35] M.B.I Raez, M.S Hussain, F. Mohd-Yasin. Published online 2006 Mar 23 “Techniques of EMG signals analysis: detection, processing, classification and application” accessed 5.05.2018, <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1455479/>

[36] Dejan Nedelkovski. “How Rotary Encoders Works and How to Use It with Arduino” accessed 6.05.2018 < https://howtomechatronics.com/tutorials/arduino/rotary-encoder-works-use-arduino/ >

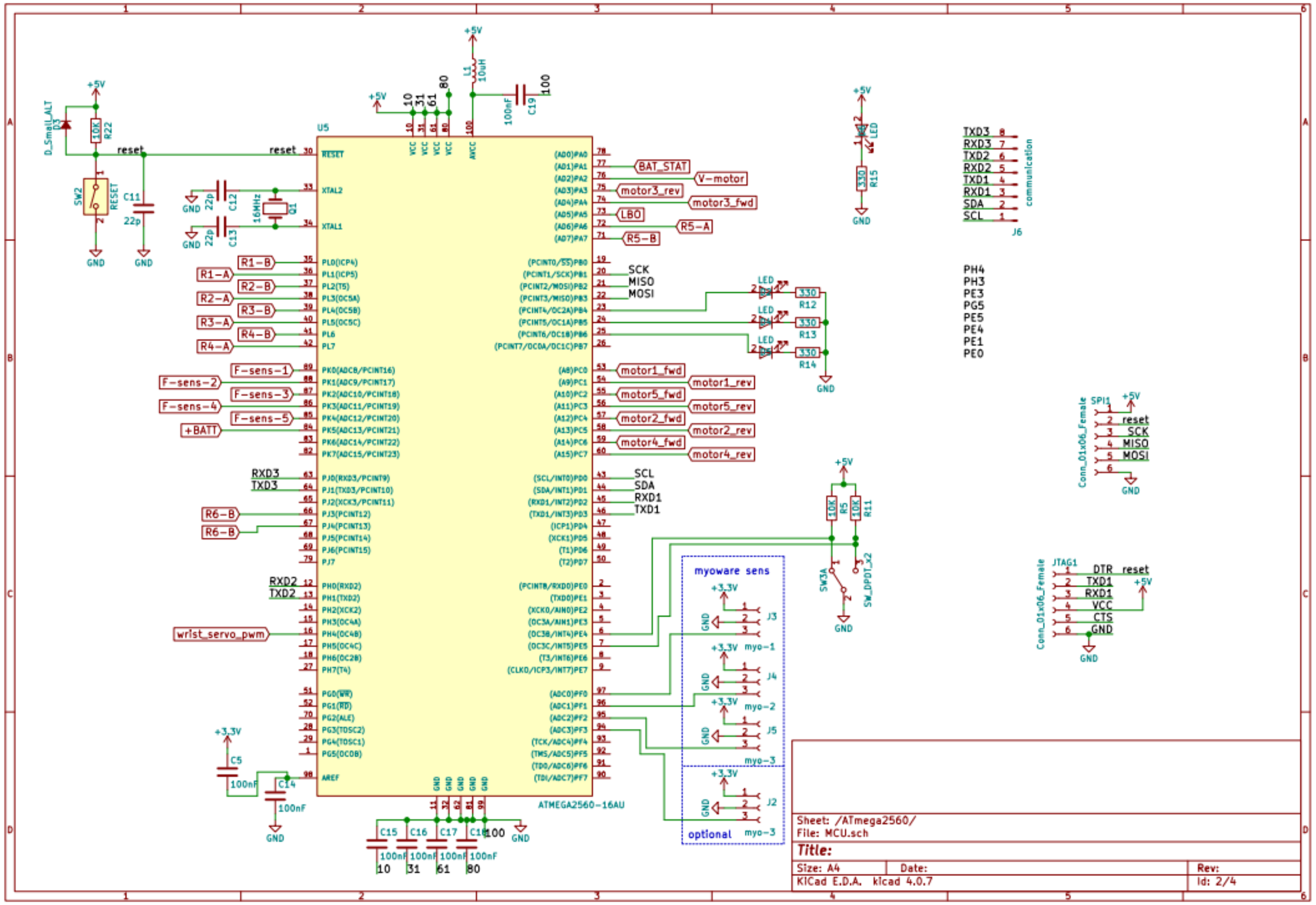
[37] Eric Coates. Published online 2017 Sep 3 “Boost Converters” < http://www.learnabout-electronics.org/PSU/psu32.php>

[38] Ngoc Tiep Nhu Nguyen. Published 2018 “Developing a low-cost myoelectric prosthetic hand”

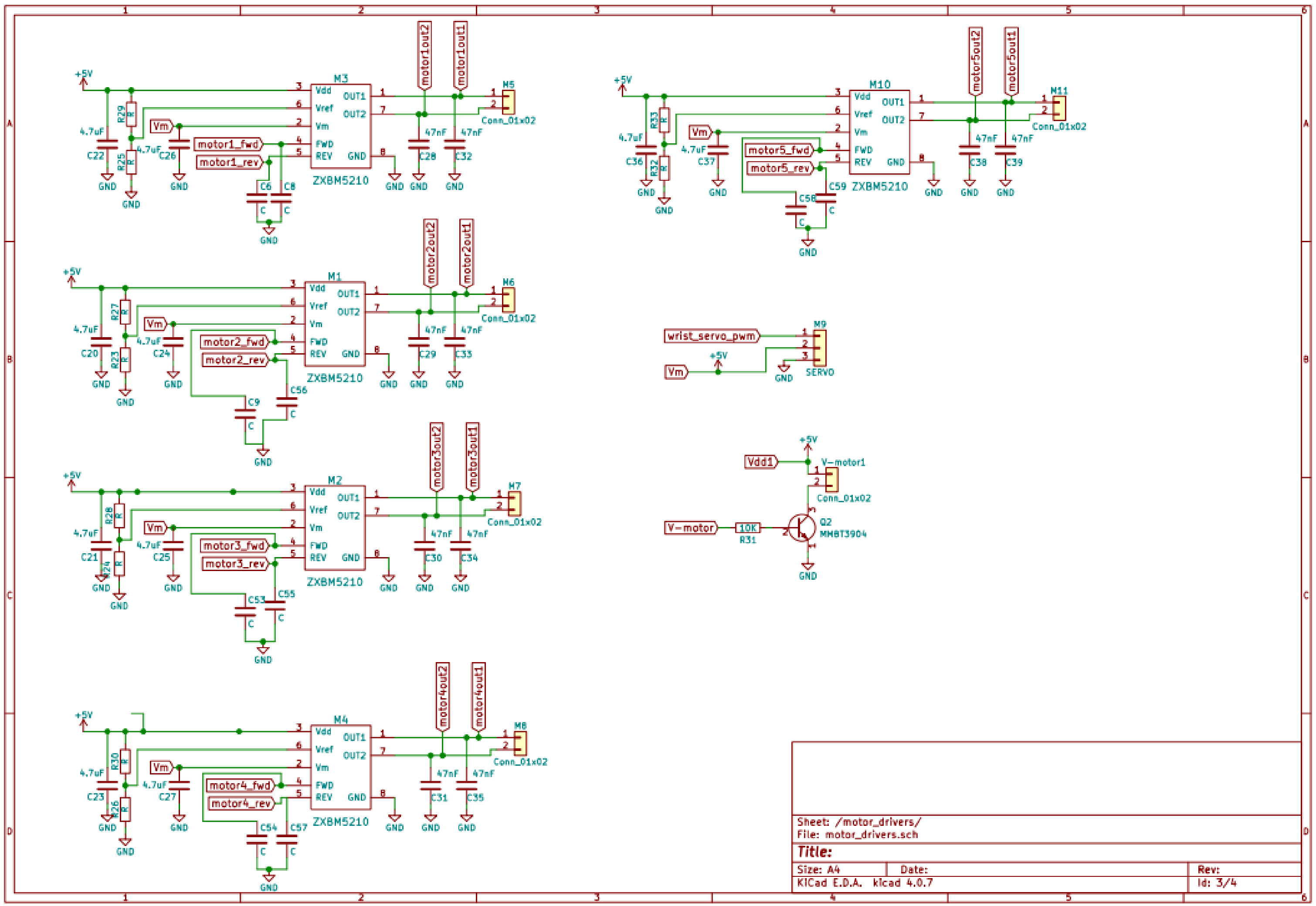
Schematic of the Myoelectric Prosthetic Hand



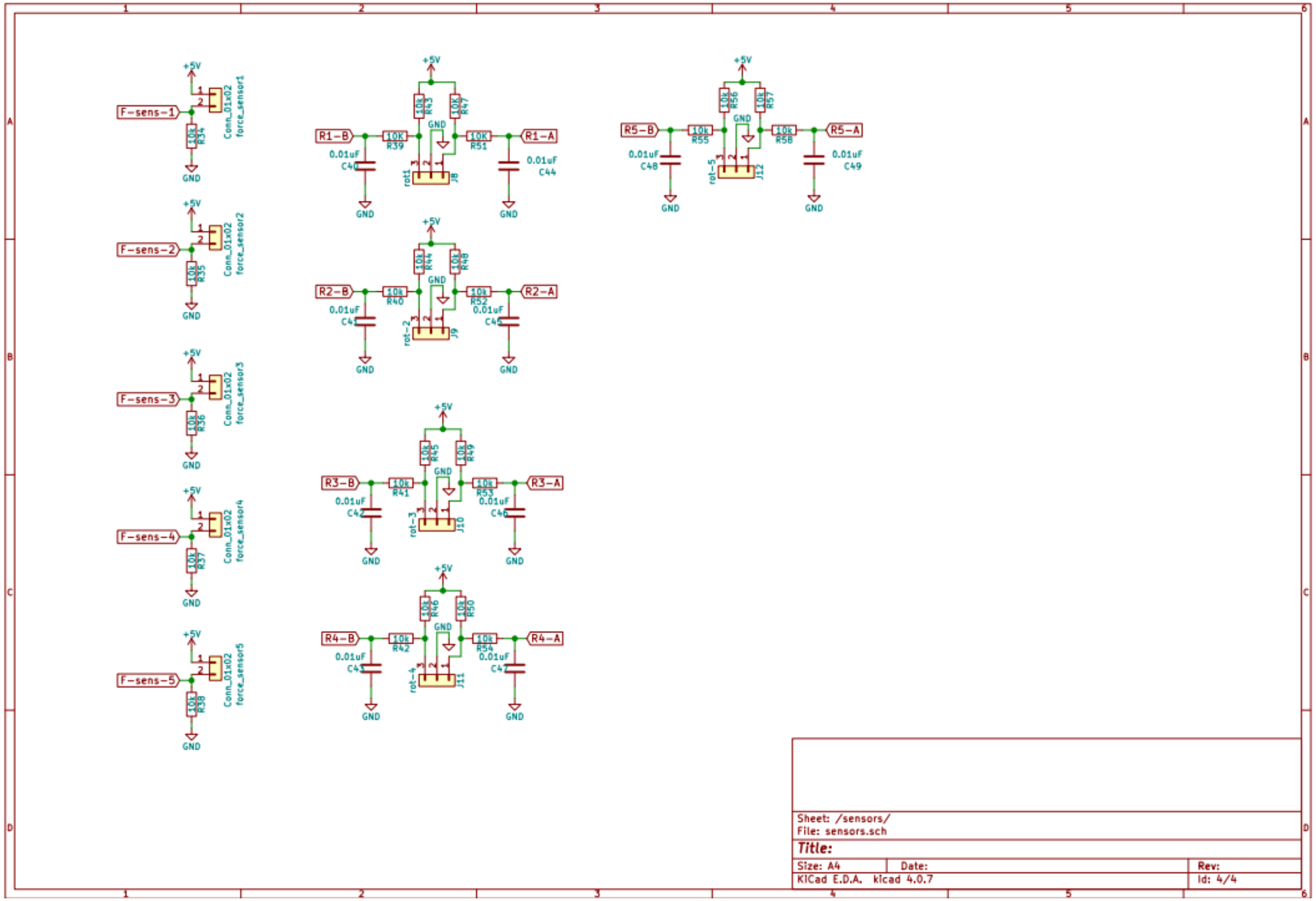
Schematic for the power management of the control board



Schematic for the MCU of the control board.

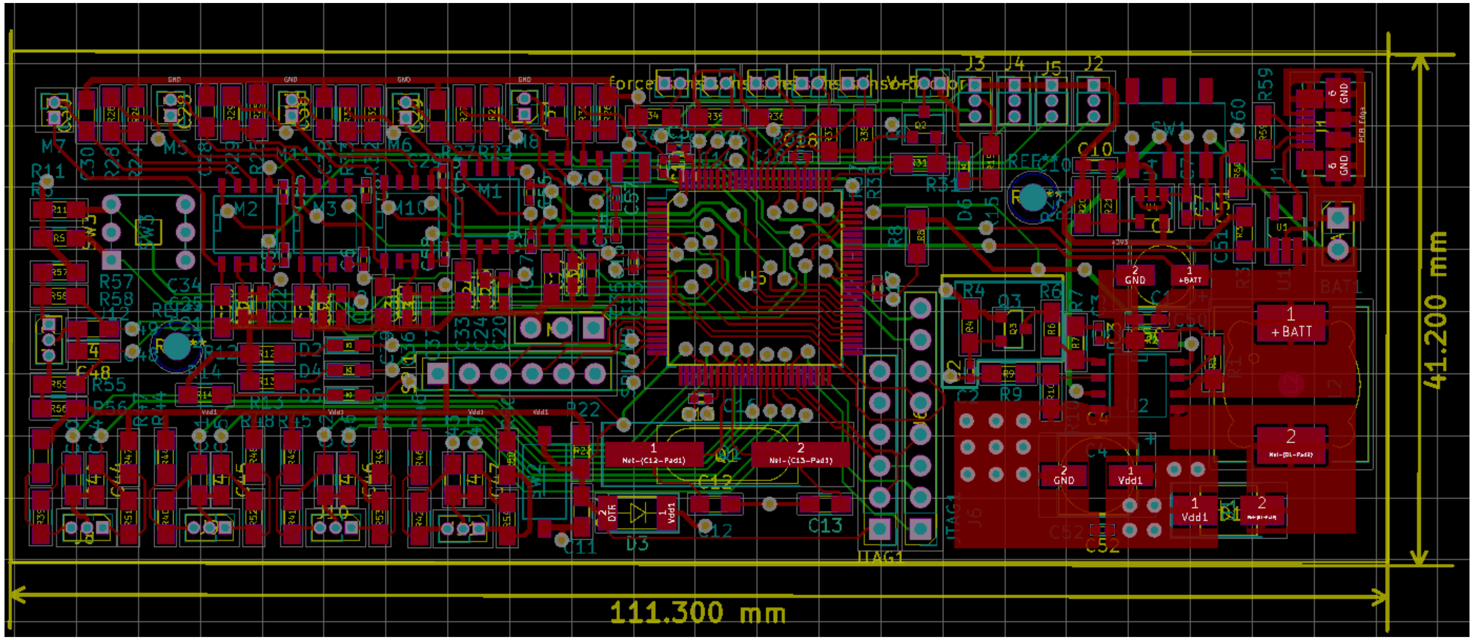


Schematic for the motor drivers of the control board



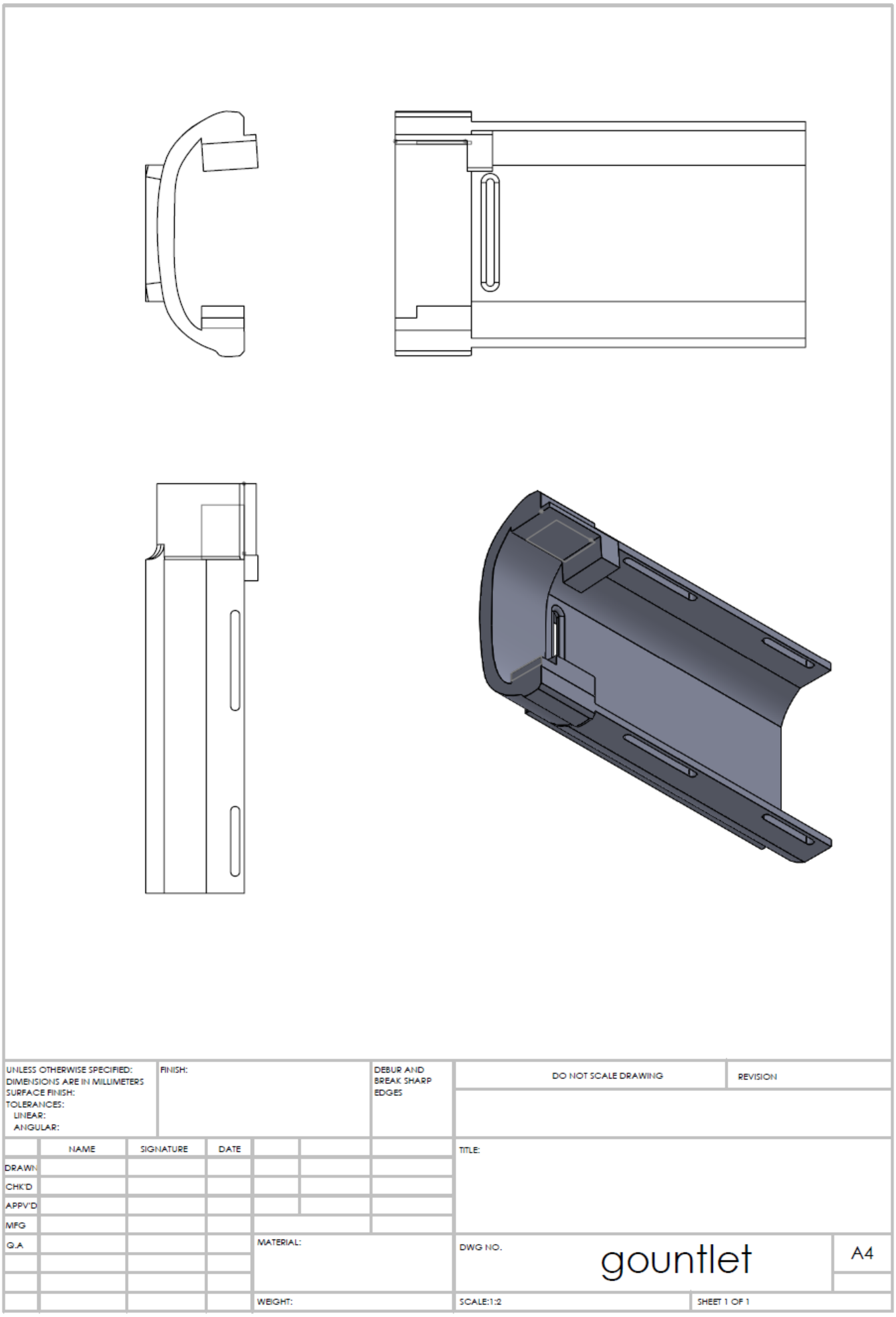
Schematic for the sensor inputs of the control board

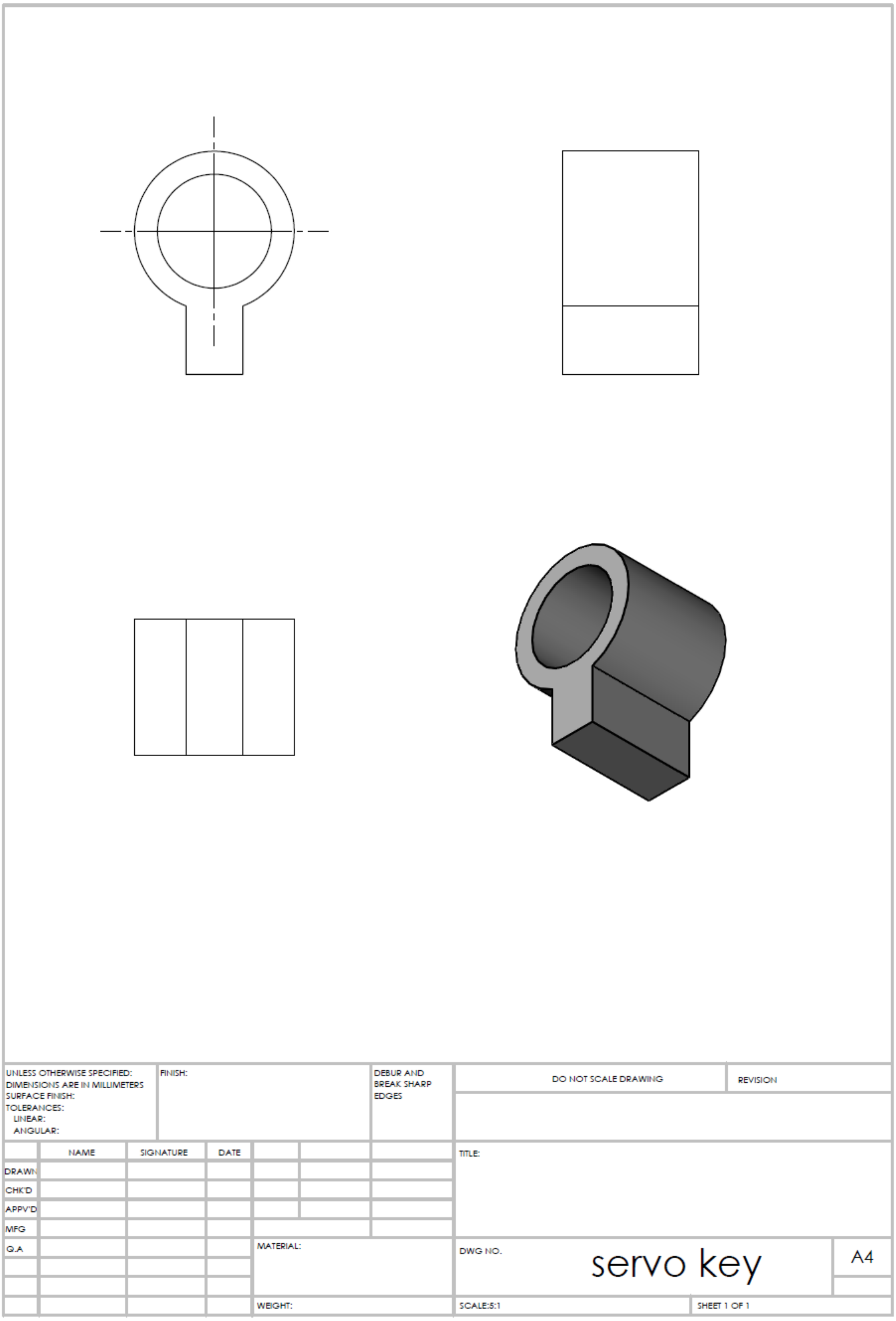
PCB board of the Myoelectric Prosthetic Hand



PCB layout the control board

Technical drawings of the extra for Myoelectric Prosthetic Hand

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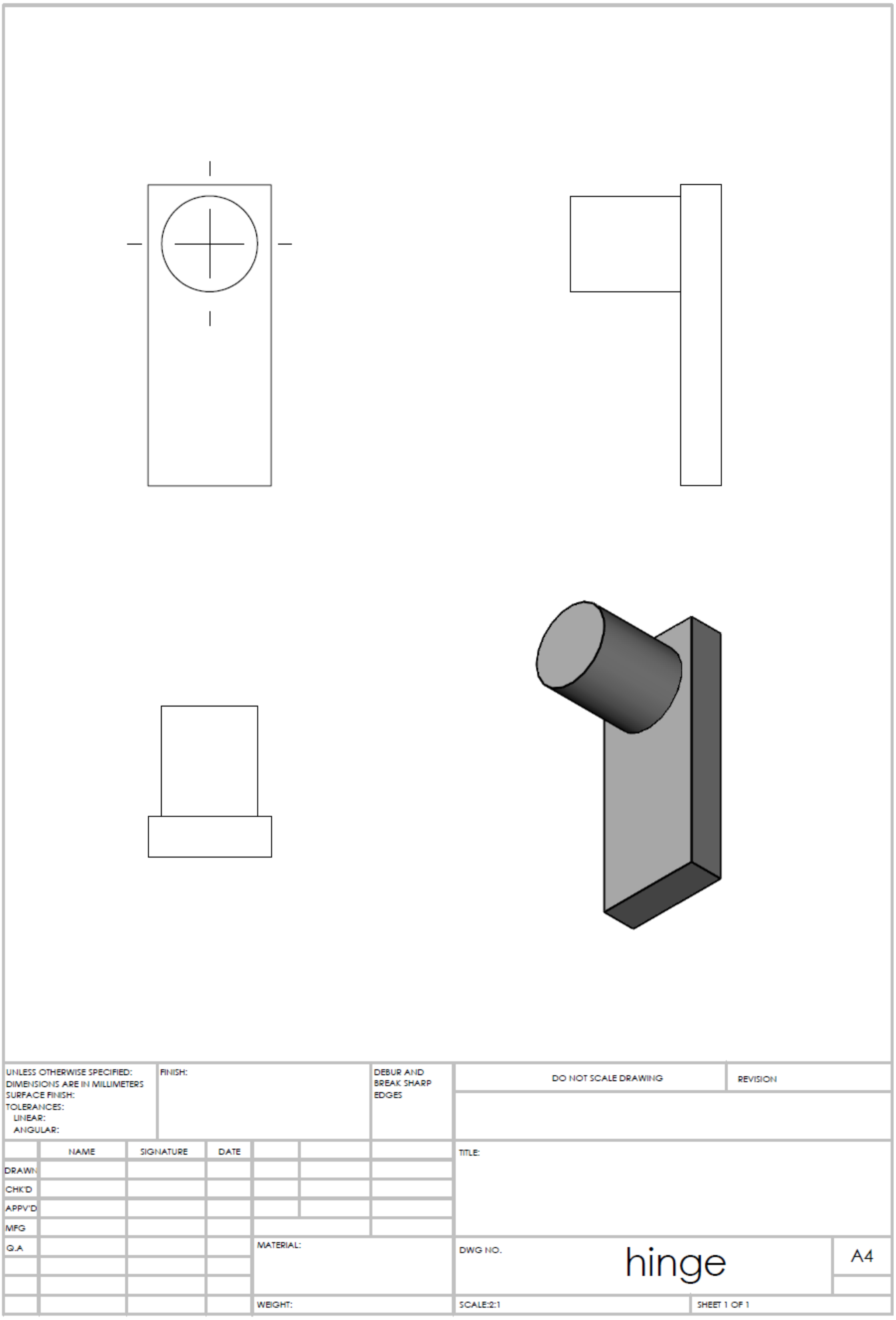
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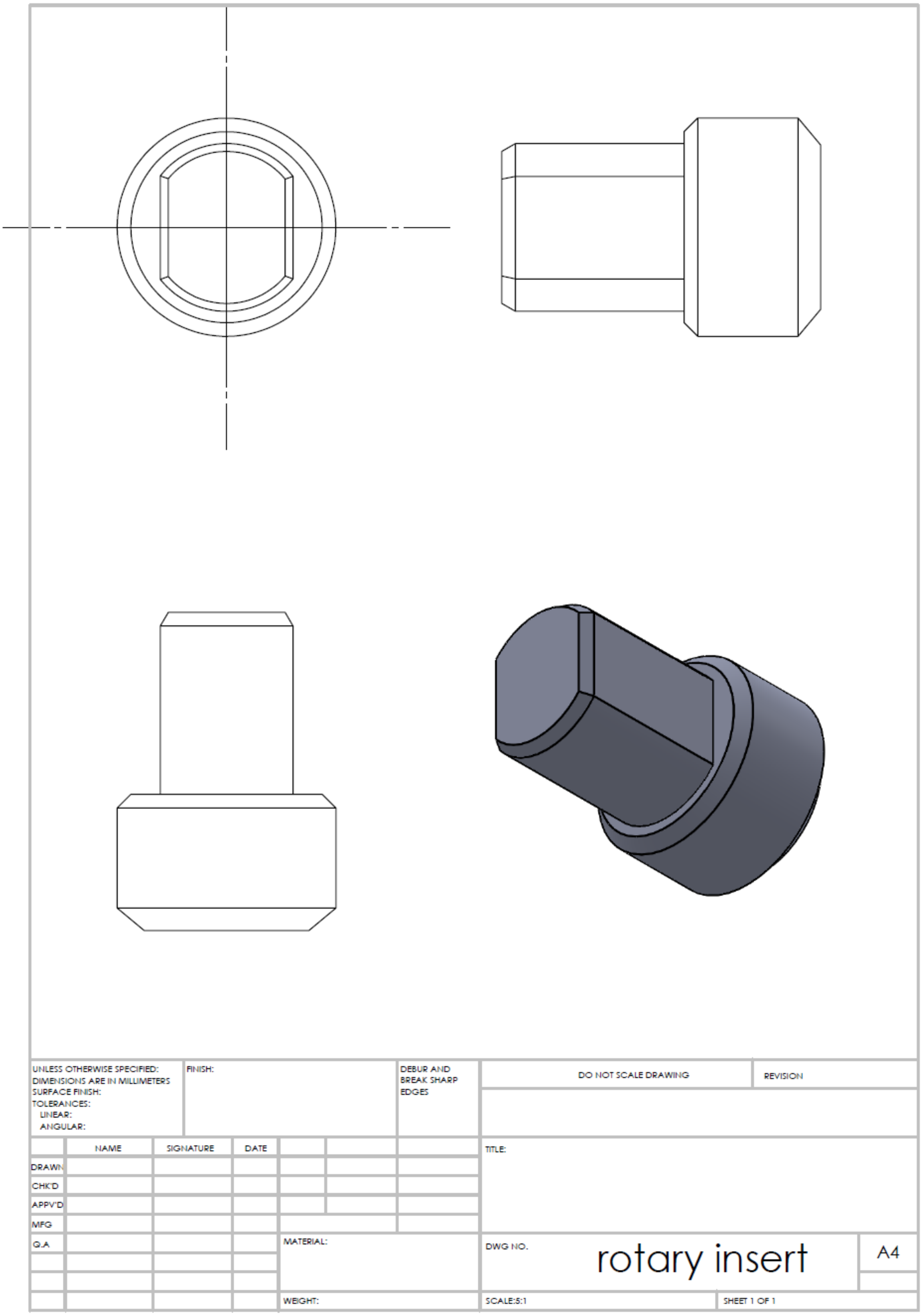
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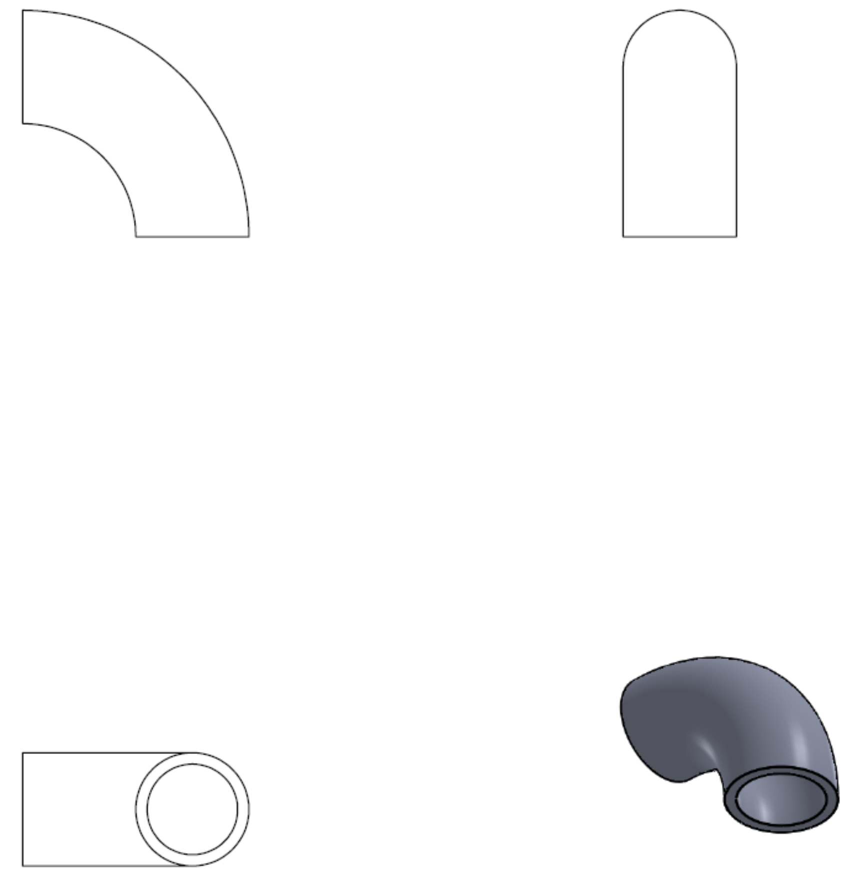

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