# Abstract

Electromyography (EMG) is the most common control interface for modern, upperlimb prosthetics. Prosthetics that make use of EMG interfaces are commonly referred to as myoelectric arms. The hands used in these devices are known as myoelectric hands. The costs of commercially available myoelectric hands are very high, ranging in price from $15,000 to $50,000 [2]. Additionally, the repair of these hands usually requires expensive proprietary components and in almost all cases, a trained professional must conduct repairs. For many amputees, in Canada and else ware, this cost barrier makes the use of a myoelectric prosthetic impractical or impossible.

At an approximate cost of $15,000, the most affordable and widely used myoelectric hands suffer from a severe lack of functionality compared to a human hand. These commonly used myoelectric hands afford the user only a single grip type: the pinch grip. The EMG control system employed by these hands allows the user to control the hands speed, but they must pay attention at all times when holding an object to avoid crushing it through accidental hand actuation.

There are hands that offer dramatically superior functionality when compared to these most affordable hands. For example, the I-Limb and BeBionic hands have individual finger movement and the ability to switch between multiple grips. However, these hands are prohibitively expensive for all but those amputees with the best funding.

Recognizing the need for an alternative to currently available technology for those with resources, we were able to develop a prototype hand with similar functionally to the more sophisticated myoelectric hands on the market while reducing the cost of the hand to well below that of the most affordable myoelectric hands that are currently available. Our team's low-cost objective was achieved by developing an inexpensive EMG control platform and a mechanical hand that is designed to be produced inexpensively on a 3D printer. Our goal of achieving a high level of hand functionality was achieved by implementing a user interface that allows many more hand functions to be called by the

user than current myoelectric hand control systems. This Multiple Impulse User Interface also reduces the chance of a stray muscle impulse causing unintended actuation of the hand; reducing the mental task load for the user of the device.

EMG signals are acquired from the residual limb of the user, amplified and then digitized with a high resolution analog to digital converter. A serial peripheral interface is employed to transfer the digitized signal from the analog to digital converter to a microcontroller which identifies muscle impulses and actuates motors in the printed hand. The function that the mechanical hand preforms is determined by the sequence of impulses produced by the user in quick succession. If the control logic of the hand detects a function call, it will provide haptic feedback to the user alerting them to the device status. A pressure sensor in the thumb of the prosthetic hand provides feedback to the hands control logic, reducing the risk of dropping or crushing an object being held in the device.

## Introduction

A low-cost 3D printed prosthetic hand with intelligent EMG control was designed in the department of electronics at Carleton University as a fourth year engineering design project. The team members who worked on the project were Alim Baytekin, Alborz Erfani, Natalie Levasseur, and myself. Dr. Leonard MacEachern supervised the design and manufacture of the prototype prosthetic hand. The intention of this report is to provide a technical overview of the design of the prototype that was developed. Particular emphasis will be placed on the design of the mechanical hand, the intelligent motor control logic, haptic feedback implementation, and the integration of all of the individual system components into a functional prototype.

## Background

The cost of a modern myoelectric prosthetic hand in Canada ranges from $15,000 to $50,000. The average arm amputee owns a more moderately priced device costing about $15,000 [2]. The high cost associated with myoelectric hands creates a significant economic barrier to ownership for many amputees in Canada and abroad. Additionally, hand functionality is limited among these more moderately priced devices. Many of these hands only have the ability to open and close in a single grip.

Meanwhile, the functionality afforded by high end, upper-limb prosthetics has never been greater. Products such as the I-Limb and the BeBionic hand operate using independently actuated fingers and are capable of many grips. Unfortunately, the prohibitive costs associated with these devices prevent all except the best funded amputees from taking advantage of this revolutionary technology.

There is a clear deficiency of low-cost, high functionality devices in the upper-limb prosthetics market. The goal of this project is to address this deficiency by developing a myoelectric hand that has similar functionally to the most expensive hands available at a cost dramatically lower than the least expensive hands.

In order to accomplish this goal, two parallel systems had to be developed: an in-expensive electromechanical hand that was a reasonable analog of a human hand and an inexpensive EMG based control platform. In order to keep the costs down and hasten manufacturing, the team decided that the mechanical hand components should be printed using a 3D printer. For the same reasons, the team decided that the EMG control platform should be comprised of inexpensive, readily available components.

3D Printing technology has been around since 1986 [3]. The cost associated with the technology and the fragility of the parts that were produced prevented the widespread adoption of 3D printing as a manufacturing technique. Over the past few years, this paradigm has begun to shift. Introduction of high quality consumer 3D printers, such as the Makerbot Replicator and the Bits from Bytes RapMan, have made 3D printing available to a much wider audience. There are now more than 24 consumer-grade 3D printers available for under $5000 [4]. The majority of these printers use fused deposition modeling (FDM) as their printing technique, which provides the most robust parts of any 3D printing technology.

EMG signal acquisition systems are traditionally composed of analog filters and gain stages for each channel. In order to meet our goal of using fewer components than a traditional EMG acquisition system, our team explored a newer approach to the problem. A high resolution analog to digital converter can be used to capture the signal with a resolution of only a couple hundred Nano Volts. This level of resolution allows all of the filtering to be done in the digital domain.

All of the signal processing must be performed on a microcontroller. Fortunately, the cost and accessibility of microcontrollers has been improving over the past few years. Arduino microcontrollers are still a mainstay in the inexpensive microcontroller category, characterized by their low cost and simple C++ based programing environment. Other more powerful microcontrollers are also beginning to enter the market. The fastest Arduino currently available, the DUE, runs at a clock frequency of 84MHz. Even more speed can be found in the Beaglebone, a new, Arduino-sized microcontroller that operates at up to 700MHz.

As the quality of, and access to advanced components and manufacturing techniques improves, many previously specialized applications will begin to see lower cost alternatives. One of these areas of growth is prosthetics and our 3D-printed prosthetic hand exemplifies that trend.

## Prosthetic Hand Overview

The low-cost prosthetic hand developed for this project consists of four primary components: a 3D-printed electromechanical hand, an EMG interface, a microcontroller capable of real-time signal processing, and a stable embeded control system. The 3D-printed hand prototype was modeled, printed and assembled for less than $250. The hand contains over 30 components, including 15 unique printed components. It is actuated with high-torque hobby servos that are controlled by pulse width modulated (PWM) signals regulated by the microcontroller, an Arduino Due. Figure 1 shows a basic overview of the hand's electronic control system.

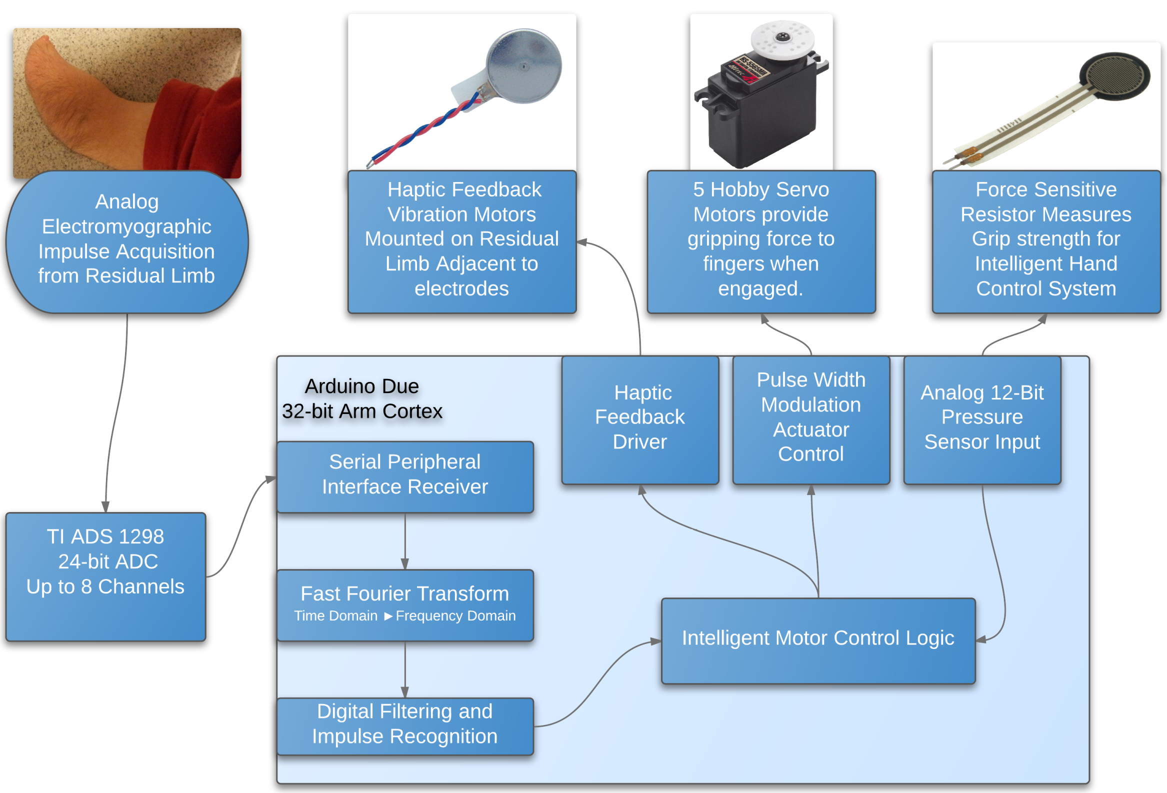


Figure 1: Top Level Overview of the Electronic Control System for the Prosthetic Prototype

The EMG interface works by acquiring differential signals from muscle impulses in the residual limb of the user. Those signals are then amplified, and pass them to a high resolution analog to digital converter (ADC). The ADC then outputs the signals over a serial peripheral interface (SPI) to the microcontroller.

The Arduino processes the signals by preforming a Fast Fourier Transform (FFT) which converts the signals from the time domain to the frequency domain. Once a signal is in the frequency domain, the magnitude of the relevant frequency bins can be calculated. If the magnitude of these relevant bins exceeds a threshold value, a muscle impulse is said to have been detected on that channel.

Control logic embedded in the microcontroller captures combinations of muscle impulses across all of the available channels, henceforth known as opcodes. The control logic analyzes sequences of opcodes, and actuates the motors in the hand in order to perform the function dictated by the given opcode sequence. This novel method of using sequences of opcodes to dictate prosthetic hand function is called a Multiple Impulse User Interface (MIUI).

A pressure sensor that resides on the gripping surface of the prosthetic thumb provides feedback to the microcontroller through an onboard ADC. This feedback is used to control the pressure that is applied when the prosthetic hand grips an object. The control system is also equipped with a haptic feedback system, that causes small motors to vibrate in response to a successfully received command.

## Theory of Operation for Multi-Input System

Our hand uses a pattern based recognition system, herein referred to as the Multiple Impulse User Interface (MIUI). MIUI works by receiving and interpreting combinations of very short EMG impulses and carrying out a pre-determined sequence of commands. For example, if the user had a two electrode channels, Channel A and Channel B, then a possible code would be A-B. This could be the code for the ”Soft-Grip” function that closes the hand around an object until it has a firm, but non-crushing grip. The integrated pressure sensor provides feedback about grip strength and the motor control logic maintains a firm grip, even in the case where there is some slippage. Once the object has been successfully grasped, the user is notified by haptic feedback and they are free to stop paying attention to what their prosthetic hand is doing, feeling confident that it will not let go unless instructed to do so by another code.

This ”Soft Grip” example is only one of many functions that can be requested with user customizable codes. The use of the ADS1298 as a front end allows more advanced users to add up to eight channels to various muscle groups on their residual limbs to improve signal acquisition accuracy and increase the number of available functions.

A major advantage ofMIUI over traditional prosthetic control schemes is the flexibility it offers to the end user. As is evident from table 1 above, the MIUI control system is customizable for each user. A child who receives their first myoelectric arm at the age of three will use a very simple control scheme that requires one or two electrodes and only a single opcode. As the child grows older, they will be able to incrementally increase the number of channels and the number of opcodes they use, increasing the functionality of their hand.

62% of child amputees who register with the War Amps are upper-limb amputees, but only 11% of adult amputees are missing upper-limbs [2]. This suggests that many arm amputees use myoelectric limbs for the vast majority of their lives, which gives them decades to gradually improve their hand’s functionality. This makes a flexible system that can grow with the user an ideal choice for those just beginning to use a prosthetic arm.

## 3D Modeling

Solid modeling of the 15 unique hand components was performed in Auto Desk Inventor. The index, middle, ring and pinky fingers are each made up of a tip segment, a middle segment and a base segment, which is connected to the palm of the hand. The thumb is composed of just two segments but sits on a raised platform away from the palm, allowing it to directly oppose the other fingers when contracted. Figure 12 shows the assembly of the printed hand as well as the hands major design features.

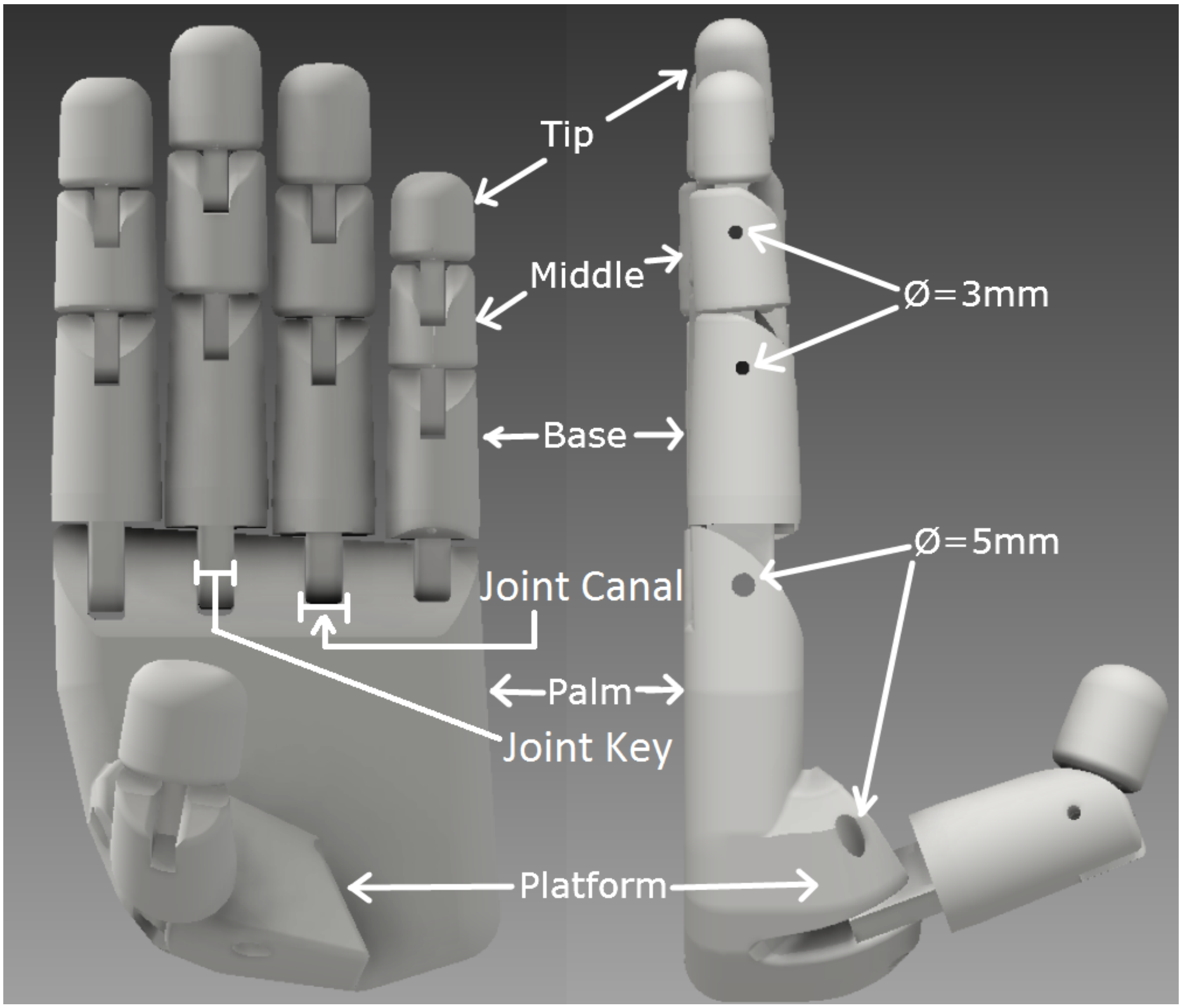


Figure 12: Prototype Hand Assembly

## 3D Printing

Upon completion of virtual mechanical simulations, the hand was ready for manufacture. The method of manufacture selected was rapid prototyping on a Fused Deposition Modeling (FDM) 3D printer. Fused Deposition Modeling, also known as Fused Filament

Fabrication is a type of additive manufacturing where a thread of molten plastic is used to trace out a layer of a part in the X-Y plane. Once an entire layer is traced, the print platform is lowered and the next layer is printed.

The prototype hand model was converted into stereolithography (STL) files in Autodesk Inventor. These STL files were loaded into the printer's software, arranged for printing, and converted to G code. G code is the control code that provides the printer with instructions regarding the velocity of the print head, extruder temperature and the filament extrusion velocity. The hand parts were printed in 18 hours on a Dimension SST 3D printer. The plastic used to print the prototype hand was Acrylonitrile Butadiene Styrene (ABS) Plastic. The Dimension SST has a layer thickness of 0.254mm.

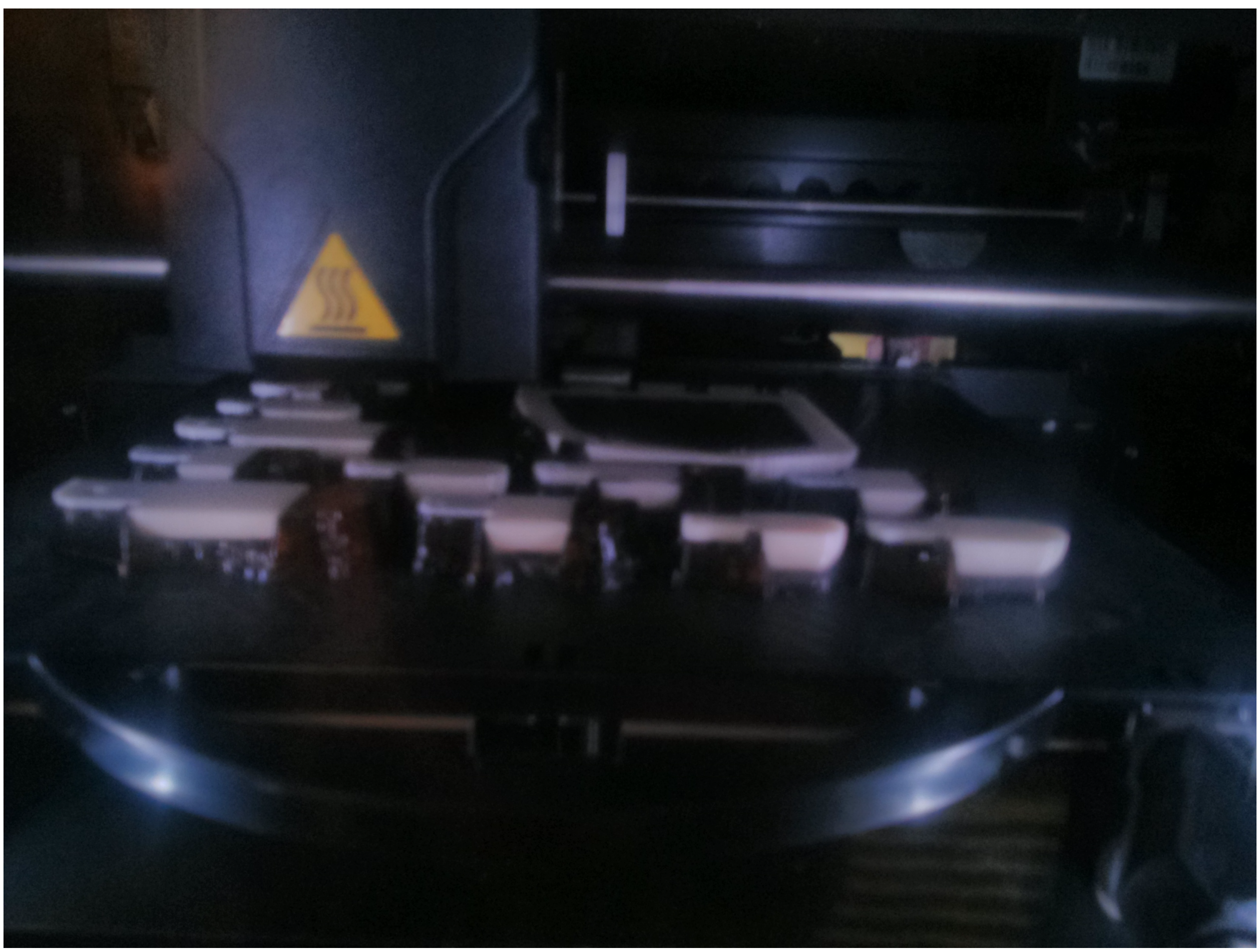

Figure 13: Prototype Hand Printing in Progress

Figure 13 shows the hand about one third of the way into the print. The white material being printed is the ABS plastic that will constitute the finished parts and the black printed material is support material that dissolves when exposed to a weakly basic solution. After the print is complete, parts are submerged in a bath of basic solution and the support material takes about one hour to dissolve away.

## Benefits of a 3D printed hand

There are two major advantages to producing prosthetic hands with 3D printers. First, it is very inexpensive. The accelerating adoption of consumer grade printers and the decrease in the price of feed stock means that replacement and upgraded parts can now be printed in many materials for only tens of dollars. Second, 3D printing allows for mass customization, a sought after quality in prosthetics. Using this technology, every hand can be designed to meet a specific users needs, including the size of the hand and its complexity. The size of each hand can inexpensively be modeled to match the proportions of the opposite hand. Also, some people lack the fine motor skills, experience or need or an advanced hand with many degrees of freedom and a myriad of functions. Due to the modular nature of the hand design, these users can use a simpler hand and upgrade individual components as they grow and their abilities or preferences change.