Design of a Bionic Hand Using Non Invasive Interface

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Abstract

The use of a bionic hand using a non invasive interface is a project aimed at restoring motor function and limited sensory information to a patient who has lost a hand or an arm. The use of an easy to use interface that gives the user control with their functioning hand simplifies daily activities that would otherwise be more difficult. Signal extraction can be acquired from the control unit using magnetic Hall Effect sensors which then act as a 2-bit binary positional system for the output of the bionic hand. Electronic circuitry must be developed to safely transmit control signals to hardware and also send appropriate output pulses to drive the mechanical system. In addition a microcontroller must be programmed for the logical control of the output with respect to the control signals and feedback from pressure sensors on the bionic hand. Important theoretical developments are discussed with a design strategy on implementing the solution. Input regulation is developed to isolate the control signals from the microcontroller to protect the user and the equipment of any possible damage. Logical programming is done on the microcontroller via C to receive inputs and act as a 2-to-4 decoder for output paths, with appropriate output pulses to the motors. In addition the programming is able to receive feedback from the hand in the form or pressure sensors that alert the user when objects are grasped and firmly held. This report concludes with a critical analysis of the results obtained and future recommendations on delivering a more accurate project.

Key words: Bionic, non-invasive human-computer interface, Hall Effect, pressure feedback, motor control, programming, microcontroller.

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Chapter 1
Introduction

1.1 Background

Bionic Hand Using Non Invasive Interface is a project aimed at delivering motor control and sensory feedback to individuals who have lost their ability. This project is a combination of electrical and mechanical systems which are user controlled. The electrical systems are there to receive inputs from physical controls and drive the mechanical system. The mechanical system is the device that provides the output to the user, but also sends feedback from how much pressure it's currently experiencing back to the electrical system. Together the two give the bionic hand that has been the basis of our work for the past six months. Since this was a joint project it was decided to split the tasks between myself and my partner, Chris Kidd. The project was split so that all things concerning the programming and feedback would be my area of focus, while all things concerning the construction of the bionic hand and control glove was to be done by Chris. The project eventually developed in such a way that gave me the opportunity to work on the following tasks: develop an input regulation circuit to protect the user and the microcontroller; program the microcontroller; develop output circuitry that was capable of driving the motors of our mechanical system; and finally design a feedback system using pressure so the user could have some sensory information whilst using the bionic hand.

It is appropriate at this point to define the purpose of this project and ask the question of why we are engaging in this project. Patients can lose their motor and sensory abilities for number of reasons. They may be involved in an accident, disease such as infarction may lead to amputation of certain extremities, and patients may also be born with congenital defects in which they are missing an extremity. In addition some patients may become paralyzed due to a number of circumstances, and lose their motor and sensory control. The quality of life for patients is drastically reduced because simple

actions that we use daily, such as eating and drinking, holding objects, and dressing all become major challenges. Confidence, self-esteem and motivation can reduce with patients who have difficulty interacting with the world around them. For this reason there is a large amount of research currently underway in designing prosthetics to assist users in their daily activities. This project was developed so that we would have a better understanding of the volume of work and the considerations necessary in designing a user controlled bionic hand. An appreciation of the design required and the ability to give a user the control of a robotic device using a simple non-invasive method were the goals upon entering into this project and are outlined further in this chapter.

This chapter will provide a description, the objectives, and approach to the problem as a whole as well as the individual work that will be presented throughout the rest of the report. Giving a complete description of the project's objectives, general approach and scope is necessary in the development of each of the parts that were individually worked on. The remaining chapters give a literature review for all the theoretical developments and design choices, a problem statement that deals with my individual contribution to the project, design procedures on how the work was designed and completed, and finally results and conclusions. Results and Conclusions will compare and contrast the observations of the project with the objectives that are presented next.

1.2 Objectives

The objectives of this project are to give the user motor control and sensory feedback information using a simple non invasive interface method. This project seeks an easy to use non invasive interface method because we felt it was important for the user to have portability and functionality. A non invasive method allows the user to wear the bionic hand only when they feel it's appropriate. The ease of use comes with the control system we have used, which is to use a control glove that reads input from flexion of the user's fingers. Two fingers are used as a binary positional system, so there is a possible of $2^2 = 4$ hand combinations. Flexion of the users' fingers must be recorded and sent to the electrical system which gives the output and direction on how to flex or extend the mechanical joints to the specified hand position. The last objective of this project is to

develop some sensory feedback to the user so that they have an idea of how much pressure the hand is on an object, or how hard a finger is pushing. It is important for a user to have this sensory information because it allows them to go beyond simple interaction with the physical world, but to understand their own interaction and the ability to make adjustments.

This project is very much qualitative as there is no quantitative value we are seeking to obtain or optimise. Objectives for the project are defined as the ability to control the bionic hand using a control glove, the ability of the bionic hand to perform up to a maximum of four hand positions that will assist the user in easing daily actions, and the ability to display sensory feedback information to the user. These objectives are relative qualities that the project should be able to perform. Specific work to this project include the creation of an input regulator which is to isolate current from the control glove to the user and microcontroller; programming the microcontroller to perform the binary positional system for output; output amplification to drive the motors from the microcontroller; and finally send feedback to the microcontroller and give this information to the user. This specific work deals with a number of quantitative issues that are developed later in the report.

1.3 General Approach to the Problem

The project is broken down into a number of building blocks that include: signal extraction from the control hand; input regulation; microcontroller; output amplification; bionic hand; and feedback. Each of these components can be worked on and tested separately without any other components, however for the project to function correctly all components must be working together to achieve the final results. The work presented in this report include: input regulation; microcontroller; output amplification; and feedback.

Signals from the control hand are obtained and the input regulator must ensure that voltage signals are properly sent into the microcontroller. The microcontroller is the brain of the project, it must receive signals associated with the user control and outputs the proper output sequences to move the joints on the bionic hand. For the motors to properly function and move the joints of the bionic hand, an output amplification state is used between the bionic hand and the microcontroller. Its purpose is simply drive the

motors using high power amplifiers from control of the microcontroller since the microcontroller will not have enough output current to drive the motors on its own. Lastly feedback from pressure sensors must return to the microcontroller so the user can have information regarding the pressure and grasp of the bionic hand. These stages are described with their theoretical developments and results in the following chapters.

1.4 Scope of the Project

Motor function can range from simple movement of a joint to complex coordination of events supplied to the human hand for many movements we use. Also the number of sensory information we can perceive with our hands such as pressure, temperature, motion, and proprioception are difficult to restore non-invasively to a user. This project is meant to deliver simple results that can help users with daily activities. Simple motion of three fingers, one in opposition with the other two, are the primary goals. Flexion and extension of the joints will be required to deliver four hand positions which are closed grasp, point, pinch, and finally open position. It was decided that these positions allow the users to maximize the actions that can be achieved such as grasping an object, pressing buttons, or holding cylindrical objects. In terms of the degrees of freedom, the user only has one which is flexion and extension of the fingers about their joints. The wrist of the bionic hand does not rotate in any direction and is completely mounted in place. The ability to restore motor movement however only requires a single degree of freedom to be worked on.

In the form of sensory feedback information, for any sense to have limited restoration there must be sensors and effecters. Touch requires pressure sensors, temperature requires thermocouples, and movement requires accelerometers. The issues when dealing with how to restore the information to the user are with the choice of effecters. There are many different methods for delivering these results such as linear actuators pressed on the user so they can feel pressure proportional to what the bionic hand is experiencing or simple methods such as pressure thresholds that give a binary result if pressure is over or under a certain threshold. For this project, pressure thresholds will be used and presented to the user visually using light intensity when certain pressure

thresholds have been reached. This is a very simple way at delivering results that the user can equate light intensity to pressure with relative ease.

Chapter 2
Literature Review

The biggest issues surrounding the design of prostheses are that an amputee who has lost an arm for example can never have it truly replaced. In designing prostheses, designs are limited and for the most part the user feels the prosthetic is unnatural in its motion, its look, or its feel. Satisfaction in modern prosthetics comes from how close a prosthetic is to reaching its ideal objectives. User expectation plays a very important role in their use of a certain prosthetic. Does the prosthetic device give the user a realistic feel and accomplish their expectations? For example, the process of grasping an object widely depends on the surface of the object [15] which makes it very difficult in designing robotic hands and arms that are capable of complex motor movements. This literature review gives an overview of the work currently being developed in modern prosthetics. As we would expect, there are many methods of achieve a prosthetic, such as using electromyography as a control method, tissue interactions with prosthetics, the response of the body to implanted prosthetics, creation of devices with greater degrees of mobility to better mimic natural motion, and finally the use of motor and sensory control through cognitive neural processes. We begin the literature review by discussing electromyography as a control to a prosthetic arm.

2.1 Electromyography Control

When using any control method for a prosthetic arm, careful design must be put into the prosthetic itself. As [16] points out, most prosthetic hands are a four finger system where one is in opposition to act as a thumb. The use of electromyography (EMG) signals arises from the fact that the nervous system sends impulses to the muscles which exhibit electric properties during their contractions. Voltages can range from -5V to 5V which is significant compared to other surface signals on the body [13]. The collection of these signals are performed non-invasively through surface electrodes placed on major

muscles. These surface electrodes are subject to noise because different motor units can be present at any given time, so to reduce nose, an alternative approach is to use invasive electrodes to measure a motor unit [13]. To identify these signals, detection must be able to retrieve signals that are up to 20Hz and are typically random in nature [13]. The signals that are measured temporally must be converted into the frequency domain using a Discrete Fourier Transform (DFT) so that the frequencies of the signal can be analysed.

The next step in EMG controlled signals is to use the signals extracted from the body to model the behaviour of the prosthetic. For example how does flexing a muscle determine how much contraction force the prosthetic hand should experience? How long should it contract for? This is solved by modelling the muscle fibres as under damped spring-mass damper system [13]. There are many methods in taking this controller and manipulating the hand and can include a proportional integrator (PI) controller. The advantages to EMG control are that once noise is reduced, there are many possible algorithms and implementation strategies that can manipulate the prosthetic all non-invasively.

2.2 Tissue Reactions to Implanted Prosthetics

Modern prostheses need to integrate with the human body. It is important that the effects of such integration be studied. For this reason there is much research into the area of tissue reactions to prostheses.

Certain prostheses are placed into the body rather than being an extremity. Over time, these implants begin to fail even though when they were initially implanted they appeared to function correctly [13]. This is an example of how tissue reaction can affect the quality of prosthetics. The reactions typically seen are inflammatory reactions, which are immune responses, elicited from the individual. The problems of inflammatory reactions are that they will degrade the material and can even compromise its function making the implant worse for the user to have. These reactions are not well understood and therefore it is important that biomedical engineers take these effects into account when designing implanted prosthetics [13].

When using robotic prosthetics that need to be implanted mainly for use as an extremity, it is very important that the materials used in the robotic device not damage the

surrounding tissue and ideally not react with it as well. Proper materials selection is important when dealing with tissue response. The proper use of materials will limit the amount of macrophages that attack the bone where the robotic device is attached. Macrophages can make bone loss occur which will loosen the attachment site and degrade the function of the robotic device.

2.3 Cellular Responses in Signal Transmission

Modern prosthesis should all be user controllable rather than stationary. This will give the user a greater range of freedom in restoring motor and sensory function that was lost. However this requires the use of sensors that may need to be placed within the prosthetic that is implanted into the user. In cases where there are internal sensors, there will be interference caused by cellular responses and interactions.

An example of a sensor that is implanted into the user is an electrode that causes stimulation [13]. Stimulation of nerves can damage nerve fibres and their axons, and also cause induction of other cells in the nervous system to become excited. Metallic sensors using electricity also can cause cellular damage to the surrounding tissue. It is extremely vital that the right biocompatible material or composite be selected when dealing with implanted sensors [13]. Sensors are used to give feedback and control to a robotic system. Sensors that are made of metal can be more subject to corrosion within the body and the ability of that sensor to perform its task over time will be diminished. The choice of a noble metal electrode has been experimentally shown to be more resistant to corrosion effects [13].

Biomedical research and tissue engineering are important aspects in creating better robotic devices that are implanted into the body. Robotic systems can be developed according to the need of the user, but the very large limited factor for prosthetics is not only the function but its interaction within the body.

2.4 Increasing the Degrees of Freedom

One area of dissatisfaction of modern prosthetic hands and arms are the degrees of freedom they use, and specifically that they are unnatural to use. Restoring control back

to users should be done in a manner that makes them feel comfortable and easy to use. It is important that designs of new prostheses be able to use a greater number of degrees of freedom to allow the users to maximize their interactions with daily objects. This section describes the work currently being done on transhumeral prostheses for above elbow amputees.

To create a better experience for transhumeral prostheses, the design of a 5 Degree of Freedom (DOF) robotic device is used. The DOF for this device are: flexion and extension of the elbow; pronation and supination angular movement about the wrist; extension and flexion of the wrist; rotation of the wrist towards the radial bone and the ulnar bone; and finally flexion of all the fingers and opposition of the thumb for the ability to grasp objects [17]. Figure 2.1 below shows an illustrative description for the five degrees of freedom.

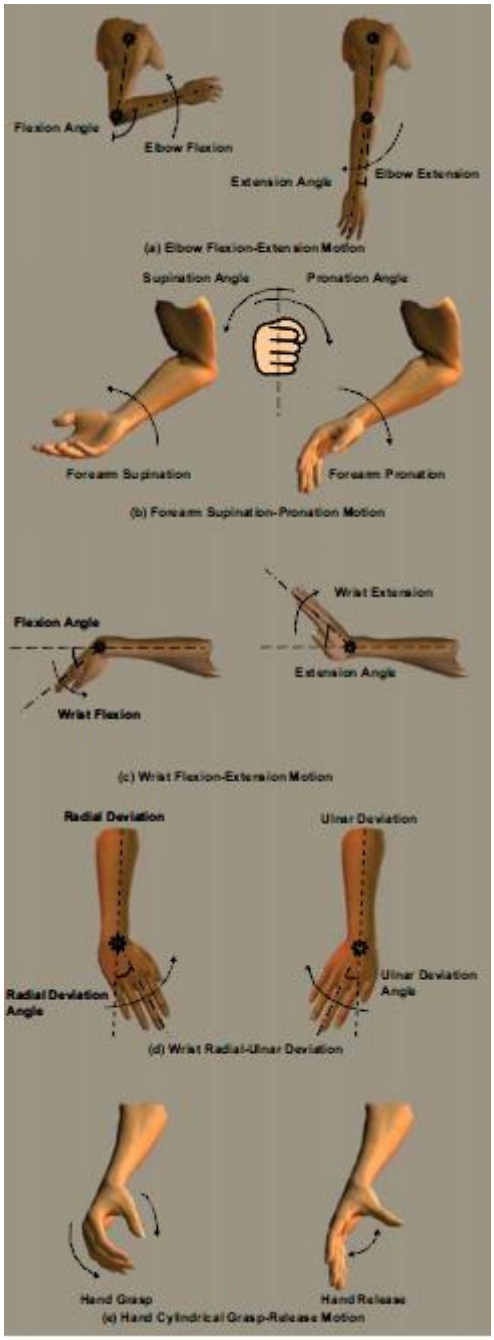

Figure 2.1: Five degrees of freedom used for a robotic device [17]

These five degrees of freedom allow the user to have an easier interaction with the world, from day to day activities such as eating, drinking, brushing teeth, and dressing. For each degree of freedom there must be an actuator capable of driving the required motor movement. This technique looks at the use of electroactive polymers and shape memory

alloys but found they did not have good enough results and had to use a traditional rotary DC motor.

The design of the robot was made so that it would look like a traditional anatomical arm which has become an important consideration for users who wear prostheses. The ability for it to look as natural as possible helps to aid the difficulty in choosing a robotic device.

The last thing to look at for adding additional degrees of freedom is the method of feedback on the actuators. This particular method in [17] uses a proportional derivative controller with a desired trajectory of the motion of the hand. This allows error to converge to zero with the appropriate negative feedback and controller. The PD controller uses a spring-damper environment to model the forces required by the actuators.

2.5 Neural Prosthetics

The last focus on this literature review is for patients who have suffered from paralysis and cannot use muscular interactions to control a robotic device. This creates a challenge to design a system that can respond to user control. Research is underway to develop methods of achieve this challenge and include cognitive control signals.

What cognitive control signals for neural prostheses do is assist paralysed patients by trying to decode intended hand signals from motor cortical neurons in the cerebrum. This is an extreme challenge to do on human patients and such this section deals with the research of decoding motor signals on monkeys. The rewards for this research are to use these techniques on human paralysis victims so that one day they will be able to have neural-motor control and greatly increase their quality of life.

The research carried out in [14] includes decoding higher level signals from three monkeys to try and position cursors on a computer screen. The goal was to have the monkeys not emit any behaviour and to record their ability to move the cursors. Over a number of weeks, their ability appeared to improve [14]. The measurements taken were measured against expected signals and include magnitude and probability. These signals were to be taken and analysed such that a goal signal, that is a signal with the intended function of movement, can be fed into a robotic device to give it motion. These signal

values can also be an indicator of a paralysed patients preference and motivation [15] which can be continuously monitored.

Chapter 3
Statement of Problem

This chapter will expand on the problems that must be accomplished in this project in order for the bionic hand to be motor operational and receive feedback. An overview of the project is given to develop the building blocks of the work that needs to be accomplished so that the bionic hand will have motor control from the user and be able to give sensory feedback to the user. These problems will be sectioned into inputs into the microcontroller, the processing program for the microcontroller, the outputs that are sent to the motors, and finally the feedback system that must relate pressure that the bionic hand is experiencing to another sensory path that the user can properly process. These four major sections will highlight the theory that is needed to understand the methodology to solving these problems which is an important aspect for the design process which is discussed in the following chapter.

3.1 Overview

In order to better understand the specific work done for this part of the project, some insight into project as a whole should be discussed. To gain a better understanding of the theoretical developments of the four major stages of the work done for this part of the project, which will result in a better designed system of stages, it is important to know what to expect in the form of input to the four major stages as well as what to expect from the output.

The control unit is a glove worn by the user that can detect flexion and extension of two fingers that will be used as input bits to the system. The process of detecting flexion and extension are done using two linear Hall Effect sensors which will output a voltage dependent on the magnetic flux, or how much magnetic field is passing through the sensors at any given moment. The amount of flux is proportional to how close a strong magnet is. The voltage results from an unequal charge distribution along

conducting surfaces [3]. Since the flux lines of a magnetic field decrease with distance, the closer the magnetic field is, the stronger the flux will be and greater the voltage. Thus we can expect that the Hall Effect sensors will output a voltage into the system dependent on distance. When a finger flexes, the magnet is passed over the sensor resulting in that sensor to be deemed on. When the magnet is past a certain distance or region away from the sensor we expect the sensor to be off.

The outputs of the system are in the form of motor control to the bionic hand that has been built. The bionic hand was build using meccano with a motor and pulley system. String was used on both sides of a finger and wrapped around a single axel (one for each finger) in opposite directions. When the axel would spin one string would tighten while the other would relax resulting in the finger to move. The opposite holds true, when the axel rotates in the opposite direction, the tight string would relax while the loose string tightens moving the finger back.

Given this knowledge, the system must be able to accept a dynamic voltage input and also be able to output to motors capable of constant rotation in two different directions. The problems faced in this project are: how to regulate the input into the microcontroller; how to process and control the bionic hand through the use of motors; and how to display sensory feedback to the user.

Figure 3.1 below shows the flow diagram of the project as whole outlining the input into the system, the output bionic hand, and the four stages which form the basis of the system developed for this project. Theoretical developments and solutions to the questions posed form the basis of the remainder of this chapter.

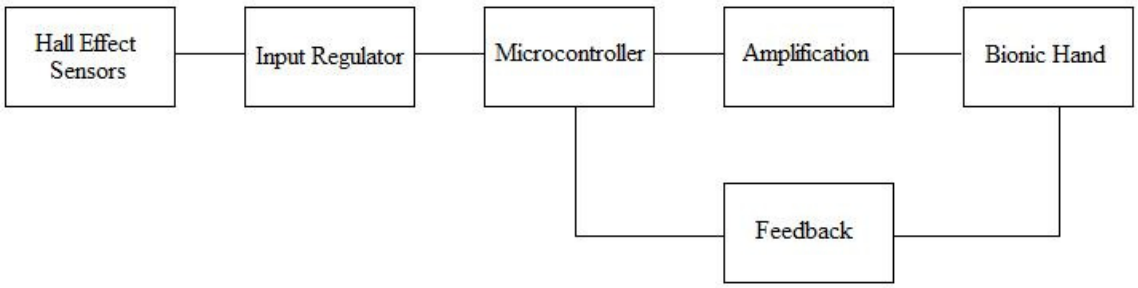

Figure 3.1: Flow diagram for Bionic Hand using Non Invasive Interface; Highlights all areas of the systems that need to be developed; Hall Sensors and Bionic Hand were supplementary to the system; Project deals with the four stages in between.

3.2 Inputs

The inputs being received from the Hall Effect sensors on the control unit are a dynamic voltage range. Since the range is dynamic and the sensors only need to be considered on or off, there must be a threshold level, meaning for dynamic voltages over a certain threshold the Hall Effect sensor will be considered on, telling the microcontroller that the user has flexed a finger on the control glove. Similarly, if the dynamic range is below a threshold voltage level, the Hall Effect sensor is considered to be off, telling the microcontroller that the user has not flexed a finger on the control glove. It is important to remember that the threshold value completely determines the sensitivity of the control unit. This is significant because we want users to have an ease of use with the control glove. If the threshold voltage level is too high then the magnet will need to be placed very close to the sensor resulting in difficulty for the user. If the threshold is too low small movements can trigger the sensor to become active which will result in undesirable affects. These must be used with a microcontroller so that the inputs can be decoded and processed as to which sensors are on and which sensors are off. This can be achieved in one of two ways: First is to accept the inputs on the microcontroller directly as analog input; and secondly through a comparator circuit that compares voltage values rather than digital values.

The first choice is to use an analog input scheme on a microcontroller that directly accepts the dynamic voltage range from the Hall Effect Sensor. This would use an analog to digital converted (ADC) to compute a digital value from the sensor output. This digital value would then be compared to a digital threshold value to see if the sensor was on or off. The second method is to use external circuitry that involves a comparator to compare the sensor output to a voltage threshold rather than a digital threshold. Comparators typically output only two values which would mean this could be entered into a microcontroller as digital input rather than analog input.

In terms of complexity the first choice is easier, using an ADC on the microcontroller for threshold measurements. On an 8-bit microcontroller voltage levels ranging from 0V to 5V are typically converted to a digital value ranging from 0 to 255. This gives sensitivity of 5V / 256 bit = 0.0195 or approximately 0.02 V/bit. Threshold voltage levels can easily be determined and adjusted simply by dividing the voltage threshold V_T by 0.02 V/bit. The second method is more complex because a comparator requires physical voltages to be measured. This requires different combinations of resistor values if we wanted to adjust the sensitivity of the control glove. The use of a comparator does have two distinct advantages however. First it allows the input into a microcontroller to be digital rather than analog which is beneficial since small microcontrollers typically have more digital input/output pins than analog pins. Since this project should be portable we want to use smaller microcontroller kits. The second advantage is that is allows isolation between the control glove and the microcontroller. The control glove should be isolated from the electronics which means that current should not flow directly from the control glove to the microcontroller and vice versa [4]. This safety feature is important because the control glove is physically attached to the user, and if the microcontroller or Hall Sensors were to stop functioning correctly, current could enter the user or the sensitive equipment could overheat and burn the user. Obviously the first method does not achieve this, since the Hall Effect sensors are directly connected to a microcontroller and for this reason, external circuitry should be developed to regulate the input and measure against the threshold voltages. This circuit is called the Input Regulator. The Input Regulator must act as a comparator against voltage threshold and isolate current, for this reason we choose operational amplifiers for the comparator since the currents from the sensors and currents from the microcontroller are completely separated. The choice of operational amplifier is done using a comparison of power dissipation which yields the results from [5] that class AB amplifiers can consume less power as a comparator than class A amplifiers.

3.3 Outputs

Referring to Figure 3.1, it is seen that between the microcontroller and the bionic hand output there is an amplification stage because the motor function of the bionic hand is

done using reversible polarity motors that cannot run directly from the microcontroller. Servo motors or stepper motors can be used for this project; the only requirement for the motor control is that it can rotate in two directions. The comparison of motors are not relevant to this part of the project however the systems to be developed must be able to control the motors so it is important to have an understanding of how the motors move the bionic hand. The motors supplied to us did not have a controller mechanism available. This put a very large constraint on the project because instead of powering the motors and controlling them separately, the microcontroller would have to control the motor through the power connections. This is not ideal because the motors were not power efficient. Tests of the motors supplied for this part of the project resulted in that they would only function when the current entering the motor exceeded 200mA. Most microcontrollers simply do not have that much output current which was the requirement for the amplification stage [3].

Control of the motors was done using the two power connections. When a high powered signal was connected to the first motor pin and 0V connected to the second pin, the motor would rotate counter-clockwise. When the high power signal and 0V were reversed on the motor pins, the motor would spin clockwise. If both were high or both were low the motor would not run. To control the motors it is evident that we need two pins off the microcontroller for each motor. One pin controls the high pulse and the second pin controls the low pulse. Alternating high and low pulses will result in the motor to alternate the direction of its rotation.

The connection between the microcontroller and motor can be done using a one-to-one mapping of the pins through an amplifier. Figure 3.2 below shows the process of how to use two digital pins on the microcontroller to control the rotation of the motor.

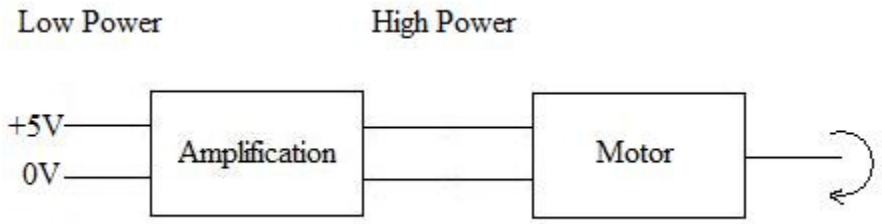

Figure 3.2: Amplification stage used to power the motors from the microcontroller

Referring to Figure 3.2 above, the amplification block is not a single amplifier but rather two for each pin. Since each pin will eventually alternate their high and low pulses, two amplifiers are required. Only one pulse will be amplified because the 0V pulse will remain the same entering the motor.

The second solution for the output was to use a metal alloy that would contract when current was placed through it due to the generation of heat. This was an example of a shape memory alloy that would be used to move the joints under the control of a microcontroller similar to the motors. This would act as the muscle tendon complex and contract when there was current entering the wire, resulting in the flexion of a finger on the bionic hand. An amplification stage is also needed because to operate the muscle wire there would need to be at least 180mA [6]. The amplification stage needs to be developed regardless of which output method is used.

3.4 Sensory Feedback

To restore sensory feedback to the user there needs to be two stages to this problem. First there needs to be sensory information from the bionic hand that the user is missing such as force, temperature, and proprioception. Secondly there needs to a way to relate the sensory information back to the user through some other sensory pathway that the user can experience and process correctly. To tackle these issues we need to develop an understanding of how to receive information from the bionic hand first and then look into possible ways of easily giving the information back to the user.

The three main senses missing after the loss of a limb are touch, temperature, and its relation to the body. With touch, we can use the piezoelectric effect which will induce a current i, that is proportional to the rate of change of the deflection of the crystal [7]. Since current is also the rate of change of the charge with respect to time we can relate the deflection x with the following equation:

$i = dq/dt = Kdx/dt$

When using piezoelectric sensors there will always be leakage resistance and capacitance, cable capacitance and amplifier capacitance. These effects are all in parallel given their

independent nature. As a result Figure 3.3 below shows that we can develop a circuit description for the voltage of a piezoelectric sensor.

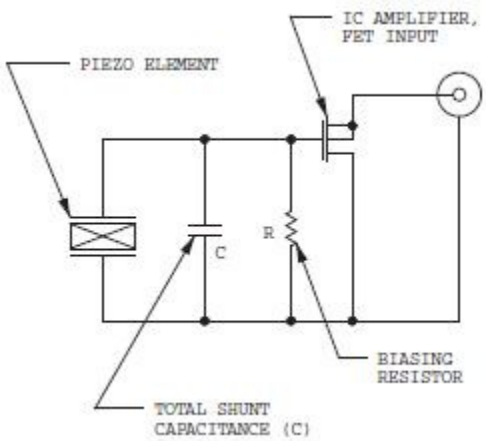

Figure 3.3: Circuit Diagram of a Piezoelectric sensor's output voltage [8]

To analyse the output voltage we need to know the current across the resistor R which is the leakage resistance, which is also equal to the voltage across the capacitor C. The capacitor C is the sum of the leakage, cable, and amplifier capacitance. Appendix A.2 analyses the output voltage of this circuit and the results are the output voltage acts as a first order high pass filter with a time constant of RC [7]. This simply means that more deflection or pressure on the crystal will have to be done more quickly than lower pressure. This adds a higher frequency component to the signal and thus increases the output voltage.

The output voltage is not given from the sensor but rather a resistance. The more force the sensor has the lower its resistance will be and vice versa. Thus we can receive information regarding touch through the use of piezoelectric sensors. The sense of temperature can be achieved through thermocouples that give the Seebeck Voltage, E as a power series with the temperature, T [9]. This voltage can be an analog input into a microcontroller if temperature was a sense to be developed. The last sense is proprioception which is difficult because as [10] shows true proprioception comes from receptors in muscle joints, muscle tissue and Golgi tendon organs. Since our bionic hand won't have artificial tissue, proprioception is a difficult sensory function to restore.

Sensory information from force or pressure can be given back to the user visually using a standard LED and the output of the sensors. This is a qualitative way of allowing the user to see how much pressure the bionic hand is experiencing by grasping an object. When there is greater force on the sensors we want the LED to become brighter than when there is less force. This qualitative scheme was chosen since visual information can be processed very quickly. A simple glance at how bright an LED is will show the user approximately how much pressure their hand is experiencing. The drawbacks to this method are that it is not a quantitative value and thus no way of telling the user exactly how much pressure is given. The user will have to learn how much light intensity corresponds to how much pressure through repeatedly using the bionic hand.

3.5 Microcontroller Processing

The microcontroller must operate the bionic hand given instructions from the control unit. As we have seen the input regulator will give a binary range into the microcontroller so that only digital pins will be needed for the control unit inputs. From the discussion of the motors and amplification we know that each motor requires two digital pins for operation. The bionic hand was built in such a way there are only 3 functioning motors so we only need 6 digital output pins to operate the bionic hand. The microcontroller can process feedback if there are multiple sensors to be used. Each sensor's resistance would be converted into a voltage where the microcontroller would average and display the results as light intensity to the user.

Since there are two digital input pins from the control glove we can control at most four hand positions. Each hand position will have a different arrangement from the three motors. Since the only control of the motors is to send high and low pulses, in order to move the fingers to their correct positions, these pulses must be timed to stop once the motor has turned the finger enough. In order to accomplish this, each finger must have trial and error timed pulses to determine how long it takes for a certain finger to flex and how long it takes to extend. Thus there are six pulse times that need to be defined which are flexion and extension of each finger. If the user wants to grasp an object, the microcontroller must flex each finger to grasp, and each finger will have a different

flexing time. If the user wants to point, two fingers must be flexed while the other remains extended, so two flexion times are sent to the two motors.

Both of the above examples were assuming the bionic hand was in a default open position. What happens if the hand was closed and wanted to point? Either the hand would have to open again and then proceed to flex two fingers to point, or the hand should eliminate the intermediate open position and move directly to the point positron. This would require the microcontroller to track the current position the hand was in, so when a user controlled input was received it could move to that new position relative to its current position.

The alternative to timed pulses at the output is to use Hall Effect sensors on the joints of the fingers themselves. If we could give a desired angle or position of the finger, an error minimizing PD controller could be used such that negative feedback would guide the position of the finger to converge to a desired angle [11]. When this project was started, not even knowledge on control systems were known so sensors were not placed on the joints which greatly affected the quality of the project. The design of the program is discussed in the following chapter. The results of the motion of the hand is discussed and compared to using an error controller.

Chapter 4
Experimental and Design Procedures

This chapter highlights the design and experimental procedures for the aforementioned problems that needed to be solved. The chapter is sectioned into design procedures and experimental procedures. Design procedures deal with the design of the input regulator, how the microcontroller was programmed and interacted with the supplied motors, the amplification stage that was needed to drive the motors, and lastly the design of the pressure to visual feedback system. Experimental procedures deal with how all the designed stages must integrate not only with each other but with the mechanical hand and its apparatus. The mechanical device and apparatus are briefly mentioned for a full understanding of how the designed stages were to integrate with the work done by another individual. The chapter ends with a description on how to operate the device once it is operational given the control glove.

4.1 Design of Input Regulator

As stated in the problem statement the input regulator's job is to isolate the microcontroller from the control unit and provide a binary input range into the microcontroller that acts independent of the magnet flux over the Hall Effect sensor. The input regulator is to have its sensitivity to the magnetic field defined from a threshold voltage, or how close the magnetic field has to be towards the sensor to be considered a high bit. The design for the input regulator first needs a comparator and secondly it needs circuitry to be able to shift the outputs of a comparator to 5V or 0V respectively. The block diagram below shows the design configuration where each component is described and designed as to operate in the manner described above.

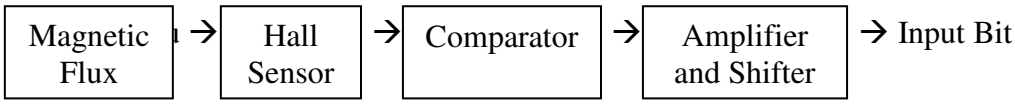

Figure 4.1: Block diagram for the input regulator showing the flow from the magnetic Hall Effect sensors to the input bit into the microcontroller.

The signals from the magnetic flux and Hall Effect sensor are assumed to be given for this project and the comparator and amplifier and shifter need to be designed. The design of the comparator is done using an operational amplifier that takes two differential inputs: one from the Hall Effect sensors and a constant threshold voltage V_T. The threshold voltage must be within the range supplied by the Hall Effect sensors which are supplied as -1V to +6V. The effects of different V_T voltages are discussed in the results section 5.1 of this report, but can arbitrarily be set depending on the chosen sensitivity of the user. For the purpose of this design we set the threshold voltage $V_T = 3V$. When the Hall Effect sensors are greater than the threshold voltage, the operational amplifier should saturate to its high supply voltage V_{CC} and when the output of the Hall Effect sensors are below threshold, that is for all outputs below 3V the operational amplifier should saturate to its negative supply voltage V_{EE}.

It is clear that the only two values that can enter the second stage which is the amplifier and shifter are the two supply voltages to the operational amplifier. The operational amplifiers used, unless otherwise specified are LF412CN amplifiers which need a minimum supply voltage 10V and a maximum of 36V. Since power consumption is an issue in this project we seek to limit the power that is used by choosing that the high and low supply voltages are $V_{CC} = 9V$ and $V_{EE} = -9V$ respectively. These values are important since the comparator will saturate to these values as specified.

The next stage in the input regulators design is the amplifier and shifter. The output values must be 5V to consider the Hall Effect sensor to be on and 0V when it is off. We can achieve this by designing circuitry that can transform the +9V to 5V and the -9V to 0V. This sets up two linear independent equations:

$$5V = 9a + b$$

$$0V = -9a + b$$

These equations can be solved trivially to be:

a = 0.2778

b = 2.5V

It is clear then that first the output of the comparator needs to be attenuated by a factor of a = 0.2778 and then added with a constant 2.5V on the product. In order to achieve these results we want to minimize the number of components and therefore the cost and labour associated with the components. Using an inverting amplifier and an inverting summation amplifier we need only three components. If we were to use a non inverting amplifier, we would need to use an extra inverting amplifier after summation to change the values back to positive. This design choice minimizes the number of components as required. The following figure shows the circuit used for the amplifier and shifter with the comparator shown on the left.

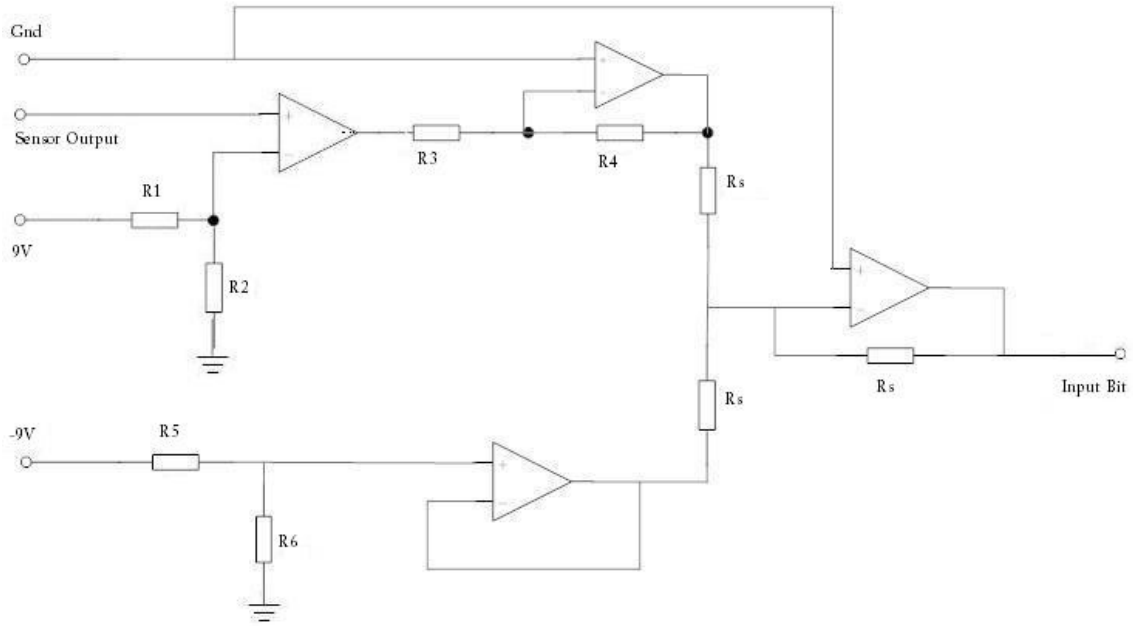

Figure 4.2: Input Regulator circuit; Resistor values R1-R6 and Rs are solved in Appendix A.1; Top-Left operational amplifier used for the comparator; Following three used for the amplifier and shifter stage.

Resistors R1 and R2 are used as a voltage divider to set the threshold voltage V_T. Resistors R3 and R4 are used for the inverting amplifier used to attenuate the signal according to a = 0.2778, resistors R5 and R6 are used as the constant b = -2.5V. We notice that b is now inverted to a negative voltage needed for the inverting summation amplifier. Lastly resistors Rs are used for the inverting summation amplifier and need to be equal and can arbitrarily be set, in this case they are set to 100kΩ. The resistor values R1 through R6 have their relationships and values solved in Appendix A.1 and are summarized in Table 4.1 below.

Table 4.1: Resistor values used for the input regulator

Resistors	Values
Resistor R1: Used for V_T	20kΩ
Resistor R2: Used for V_T	10kΩ
Resistor R3: Used for inverting amplifier	100kΩ
Resistor R4: Used for inverting amplifier	33kΩ
Resistor R5: Used for constant -2.5V	22kΩ
Resistor R6: Used for constant -2.5V	10kΩ

Using the circuit outlined in Figure 4.2, when the Hall Effect sensor is greater than threshold the comparator saturates to 9V, goes through the inverting amplifier to be come -2.5V. The inverting summation amplifier adds the constant -2.5V and inverts resulting in 5V input into the microcontroller. However when the Hall Effect sensor is below the threshold level, the comparator will saturate to -9V which is then attenuated to 2.5V. The inverting summation amplifier then adds -2.5 resulting in 0V for the input into the microcontroller.

This is the theoretical nature of the input regulator but it is important to note that resistor values play a very important role in its function and error will be introduced. The results chapter will go over the results measured against these theoretical results and its performance is critiqued.

4.2 Design of the Microcontroller Program

The microcontroller is needed to process the inputs that the user is sending via their control glove and send the appropriate output pulses to the motors that will give the bionic hand motor function. This requires that the microcontroller track the current position of the bionic hand so when an input signal is received, it can decode the signal and send the motor output relative to the current position of the hand. In addition the microcontroller must also be able to receive feedback and process this feedback.

The microcontroller program is written using C code on an Arduino Diecimila microcontroller which is based on the ATmega168 chipset. The reason C code was chosen over assembly was due to the ease of writing C code compared to assembly which differs depending on which architecture is used. C code is much more portable than assembly so the same code can be used on different microcontrollers that use similar C-based compiling systems. The ATmega168 chipset is an 8-bit chipset with 14 digital input/output pins [3].

Figure 4.3 below shows the flow diagram for the microcontroller program. The program must accept inputs and find the position of the hand corresponding to the input. The program must check to see if the new position is the same as the current position because we don’t want to send timed pulses to move the motors if they are in the correct position already. This is the importance of tracking the position with the microcontroller. The program must then send timed output pulses to each motor that must move and set the current position to the new position.

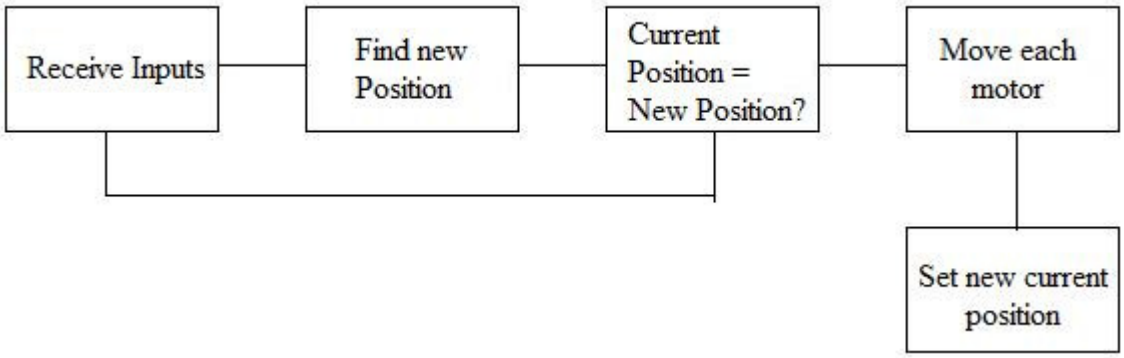

Figure 4.3: Flow diagram for the Microcontroller Program; Shows each of the five stages that must be coded for the program to work

Appendix B shows the code that runs the microcontroller program. Each block of the flow diagram has its code described next to show how each stage functions.

The first part of the code deals with setting the pin modes to inputs and outputs. As stated in the methodology section we need two digital input pins, six digital output pins. Table 4.2 below shows the pin setup so the code can be deciphered.

Table 4.2: Pin Setup for Microcontroller Program

Pin Variable	Pin Mode	Purpose
inPin1	Input	State of Hall Sensor 1
inPin2	Input	State of Hall Sensor 1
outPin1_1	Output	First pathway to Motor 1
outPin1_2	Output	Second pathway to Motor 1
outPin2_1	Output	First pathway to Motor 2
outPin2_2	Output	Second pathway to Motor 2
outPin3_3	Output	First pathway to Motor 2
outPin3_2	Output	Second pathway to Motor 3

We need two pins to control the motors, which was described in methodology. To flex a certain motor, we need to send a high voltage +5V pulse to the first pathway and a low

voltage 0V pulse to the second pathway. The +5V will be amplified and be able to rotate the motor causing flexion. Reversing the pulses yields the opposite result.

The inputs are received from the input regulator circuit as inPin1 and inPin2. These values are decoded into one of four possible states corresponding to positions 1 through 4. Then next stage is to see whether or not inputs are telling the microcontroller to go to a new position or stay the same. The position we decode is compared against value of the current position. Once these two values differ, we need to move at least one or all three motors to a new position. This is done using the function: newPosition(position, current).

This function takes two parameters: the new position and the current position. Conditional statements are put in place to see which motors need to run, which polarity to rotate, and for how long should the rotation last.

The four hand positions are: open, closed, point, and pinch. The open position is where all fingers are extended. The closed position is where all fingers are flexed. The point position is where the two index fingers are flexed leaving the middle finger extended. Finally the pinch position is where one index finger and middle finger is flexed while the second index finger is extended. The timing required for each finger is determined experimentally. Each finger requires different timing for flexion and extension and is unrelated with other fingers due to the design of the bionic hand, so all six values need to be determined. The results are shown in Table 4.3 below.

Table 4.3: Timing for the output pulses to the motors

Finger	Flexion Time (ms)	Extension Time (ms)
Left Index	450	1200
Middle	1800	3300
Right Index	1050	1350

The last part of the newPosition() function is actually moving the required motors. Now that the timing is known and how to flex or extend each motor we must develop a system that can move to a new position relative to its current position. Given four hand positions,

each position can move to 3 new positions relative to its own. This requires 4 x 3 = 12 scenarios. Each scenario is described in Table 4.4 below.

Table 4.4: Move to new position relative to current position

Current Position	New Position	Motors to Rotate
Open	Closed	Flex all three motors
Open	Point	Flex both index motors
Open	Pinch	Flex left index and middle motor
Closed	Open	Extend all three motors
Closed	Point	Extend middle motor
Closed	Pinch	Extend right index motor
Point	Open	Extend both index motors
Point	Closed	Flex middle motor
Point	Pinch	Flex middle motor; Extend right index motor
Pinch	Open	Extend middle and left index motor
Pinch	Closed	Flex right index motor
Pinch	Point	Extend middle motor; Flex right index motor

The only remaining block in the flow diagram is to set the current position to the new position just received from the sensors. This completes the microcontroller program design as all stages of the flow diagram have been described and properly designed. Appendix B shows how the design is turned in C code.

4.3 Design of the Amplification Stage

The amplification stage needs six amplifiers that can take a voltage controlled signal from the output digital pins on the microcontroller and rotate the motor. Since it was tested that the motors need at least 200mA to run, the operational amplifiers used for the input regulator will not work since their maximum power is only 670mW [12] running on at least 5V does not have the necessary amplification.

This required a higher output power operational amplifier to be purchased. Since the amplifiers were being built and prototyped on a breadboard, an 8-pin DIP was needed. The best choice that was available that had the correct amount of output current was 1A. These amplifiers were the only ones higher than 200mA needed to run the motors which unfortunately lead to greater power dissipation for the amplification stage. Each amplifier only needs to run on one digital pin, so only one amplifier needs to be designed; it just needs to be paralleled over every digital output line. Figure 4.4 below shows the use of the same non-inverting (N.I.) amplifier and how it will connect between the output pins of the microcontroller and the motors.

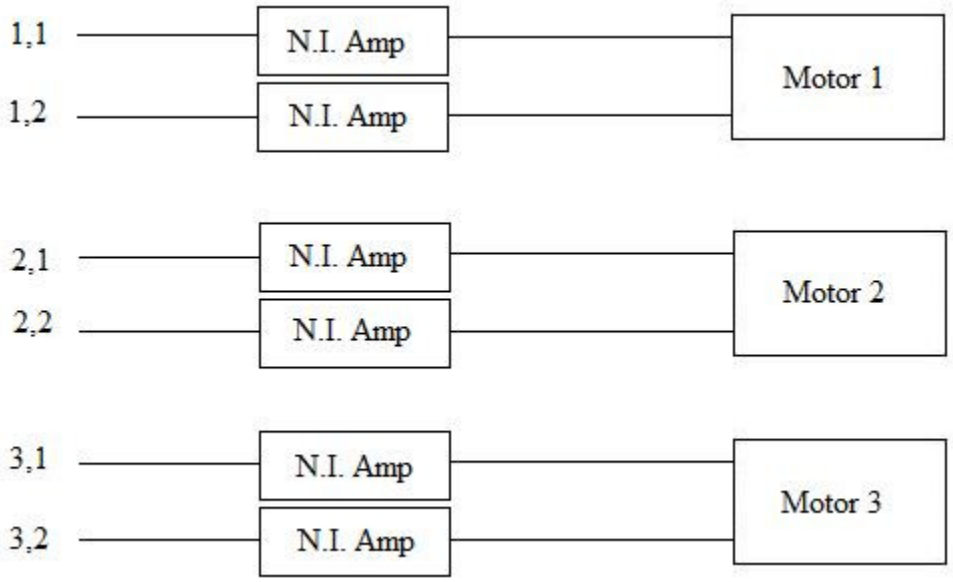

Figure 4.4: Block Diagram for the Amplification stage; Non Inverting Amplifier used to connect the motors

The design of the non-inverting amplifier is done using a standard two resistor scheme and the high powered op-amps. The voltage required to run the motors is between 6-9V so the voltage should be approximately 1.5 times to yield 7.5V which is the average of the operating voltage of the motors. Figure 4.5 below shows the configuration of the non inverting amplifier.

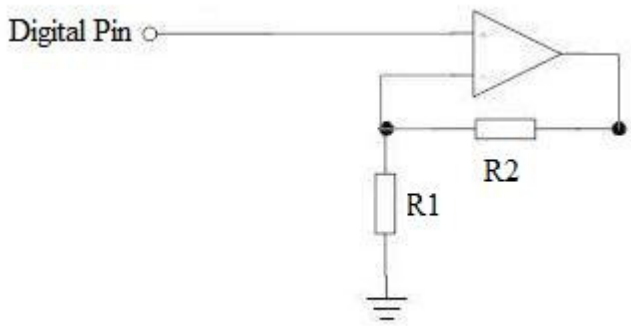

Figure 4.5: Configuration of the non-inverting amplifier

Using nodal analysis on the inverting port of the op-amp we can relate the output voltage over the input voltage as:

$$\frac{Vs}{R1} + \frac{Vs - Vo}{R2} = 0$$

$$\frac{Vo}{Vs} = 1 + \frac{R2}{R1}$$

We want R2/R1 = 1.5 – 1 = 0.5. Standardizing these values gives us R1 = 20kΩ and R2 = 10kΩ. Using this scheme whenever a digital pin is set high on the microcontroller, 7.5V with enough current to run the motor is sent and the motors should function correctly.

4.4 Design of Force Feedback

From the methodology section we know that piezoelectric change in voltage outputs a change in resistance with the force sensors. In order to have qualitative visual feedback we need to first have a voltage level that will control the brightness or intensity of an LED. Since the force sensor acts as a variable resistor, we need only to find the range of this resistance and can use a simple technique such as voltage division to control the intensity. Started earlier, when the force is at its highest, the resistance through the sensor is at its lowest value, and when there is negligible force the resistance is at its highest. This means there is an inverse relationship between force or pressure and the resistance through the sensor. Also since a low resistance should yield brighter intensity there is also

an inverse relationship between resistance through the sensor and the brightness or intensity on an LED.

To use voltage division we require that that variable resistor be placed in parallel with a resistor that has a resistance equal to about half of the range of the sensor. These measurements are discussed in greater detail the middle value of the resistance range, corresponding to a medium pressure placed on the sensor is in the range of 110-120kΩ. Figure 4.6 below shows the simple voltage division technique that can be used on each force sensor. The output of the sensor can either be directed into the microcontroller where multiple sensors would be averaged or directly to an LED.

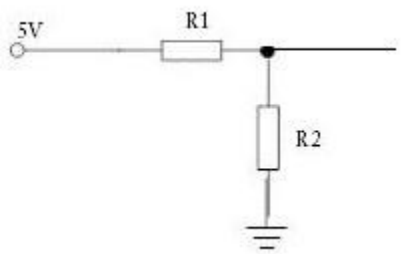

Figure 4.6: Voltage division used for visual feedback control

R2 should be set to 100kΩ as this is close to the middle value. R1 in this diagram is the variable resistance. To analyse this we note that whenever there is very little force, R1 is extremely high, on the order of MΩ and the voltage division results in approximately 0V output. When there is great force the resistance R1 drops to the order of a few kΩ and the voltage division results in a much greater output voltage closer to the 5V source. It is clear that intensity based on resistance is achieved.

4.5 Experimental Procedures

The remaining section of this chapter deals with how do integrate each of the four stages designed above into one fully functioning unit that works with the bionic hand and the control glove.

The Hall Effect sensors must be powered with a +5V source and ground. The output wire of the sensors must be connected into the input of the comparator in the input

regulator stage. Each Hall Effect sensor must be connected to an individual input regulator, meaning for every sensor there is an equal number of input regulators. In this project two Hall Effect sensors were used and two circuits were developed according to Figure 4.2.

The input regulator has one output that connects to a digital pin in the microcontroller so two digitals pins must be used. In order for the microcontroller to properly process the input, the ground on the input regulator circuitry must be the same ground used on the microcontroller. For this reason the microcontroller must be powered using the same V_{CC} and ground supply as all other circuitry, or else the voltages will be measured wrong with respect to one another and the outputs will not send.

On the output side of the microcontroller the digital output pins can connect into any of the six non-inverting amplifiers for they are all equivalent. Special care must be taken that the outputs of each amplifier connect to the motors correctly though. The outputs of the amplifiers corresponding to outPin1_1 and outPin1_2 must be connected to the middle motor. OutPin2_1 and outPin2_2 must be connected to the left index motor and finally outPin3_1 and outPin3_3 must be connected the right index motor. Since the motors are polar inputs they have red and blue inputs which are high and low respectively. All amplified output signals ending in '_1' must enter the low connection where all amplified output signals ending in '_2' must enter the high connection.

Following this setup procedure is integral to the performance of the bionic hand. Failure to follow the setup will result in incorrect motors moving in incorrect rotational directions.

Chapter 5
Results and Discussion

This chapter gives an in depth look at the results from each stage that was designed and discussion of their performance. The chapter is sectioned into results and discussion for the input regulator, the force to visual feedback system, the amplification stage, and finally the results of the entire unit. The results of the microcontroller are a projection of the results of the unit as a whole, from the control hand to the bionic hand output. A critical discussion of the performance of the entire unit is given to see whether or not the objectives outlined in the introduction were accomplished and why or why not certain objectives could not be reached.

5.1 Results of the Input Regulator

The input regulator has three goals: define the sensitivity of the control unit by means of the threshold voltage levels, create a binary input range into the microcontroller of +5V and 0V depending on the Hall Effect sensor, and isolate current flow between the control unit and the microcontroller, and. The results of each goal are described in this section.

Controlling the sensitivity of the control glove is done by setting the threshold voltage level according to how close the magnets have to be for the sensor to read their value as close enough and send an input pulse into the microcontroller. At this time it is appropriate to define a radius of approximately 1cm around the sensor to describe the position of the magnet. Table 5.1 below shows the sensor voltage, comparator voltage and input regulator voltage when the sensor is in the presence of the magnetic field. The position of the magnet is a qualitative description of how close that magnet has to be to turn the sensor on.

Table 5.1: Input Regulator results with different voltage thresholds in the presence of an applied magnetic field.

VT (V)	Sensor Voltage (V)	Comparator Voltage (V)	Input Regulator Voltage (V)	Position of the magnet
3.3	3.4	8.92	5.12	Magnet has to be applied along the radius of the sensor range
3.75	3.8	8.91	5.12	Magnet needed to be applied within the radius of the sensor range, but distinctly over the radius.
4.0	4.1	8.92	5.12	Magnet needed to be applied to half the radius between the outer boundary and the sensor itself
4.3	4.4	8.92	5.12	Directly over the sensor

In the absence of the magnetic field we expected that the comparator would saturate to the low voltage supply V_{EE} and the input regulator would output 0V. Without the magnetic field the comparator output was -8.79V and the input regulator output was 0.153V.

From the table, the Sensor Voltage was measured as the voltage required to input a high bit into the microcontroller. This should just exceed the threshold level since it needs to be greater than threshold. For every threshold voltage, the sensor voltage agreed with the threshold level, all of them being on the order of 10mV higher than threshold. The comparator voltage should theoretically output V_{CC} = 9V for all threshold levels. While the comparator output is constant as required, the output is 80mV lower than expected which will introduce errors in the input regulator. The input regulator should be 5V for all threshold levels that are exceeded. We can see that the comparator outputs 5.12V which gives an error of approximately 2.4%. This error is most likely introduced due to the standardizing values of the resistors. The resistor relationships are not met completely since there are errors in tolerances as well. Since the output error of 2.4% is less than the resistor tolerance error of 10%, the input regulator completes the objective of creating a

binary input range into the microcontroller for high pulses. At low pulses the output of the input regulator is 0.153V which is higher than expected however the microcontroller does accept this as a LOW digital voltage.

The sensitivity of the sensor to an applied magnet field is important when using the control hand. For this reason we selected a voltage threshold of 3V so that the user could flex their finger and the magnet could be placed roughly 1cm away from the sensor. This was selected as when the finger is not flexed it was far enough away that the sensor would not pick up enough magnetic fields to activate the sensor. It was also high enough that the user could have small movements of the finger without activating the sensor as well. The control glove should be an extension of the users functioning hand and should not limit them. If the user has to keep their functioning hand completely still to avoid triggering the sensors then this is not achieved. The threshold level is low enough that the user does not need to worry about placing the magnet perfectly over the sensor every time they wish to send a position to the microcontroller. The 1cm flexibility allows the finger to flex, trigger the sensor and send the input into the microcontroller with great ease. The input regulator is therefore defined by its sensitivity and the output is independent of the magnetic flux. This ensures that if the sensor is outputting -1V with no magnetic field, no negative voltage enters the microcontroller.

Testing the input regulator at 3V should yield a step function from 0 to 5V whenever the threshold level is reached. The actual results differ somewhat based on the results in Table 5.1. Figure 5.1 below shows the theoretical and experimental results of the input regulator voltage as a function of sensor voltage. The sensor output is the independent variable, and the input regulator voltage is measured at every 0.5V in the range of the sensor (-1V to 6V).

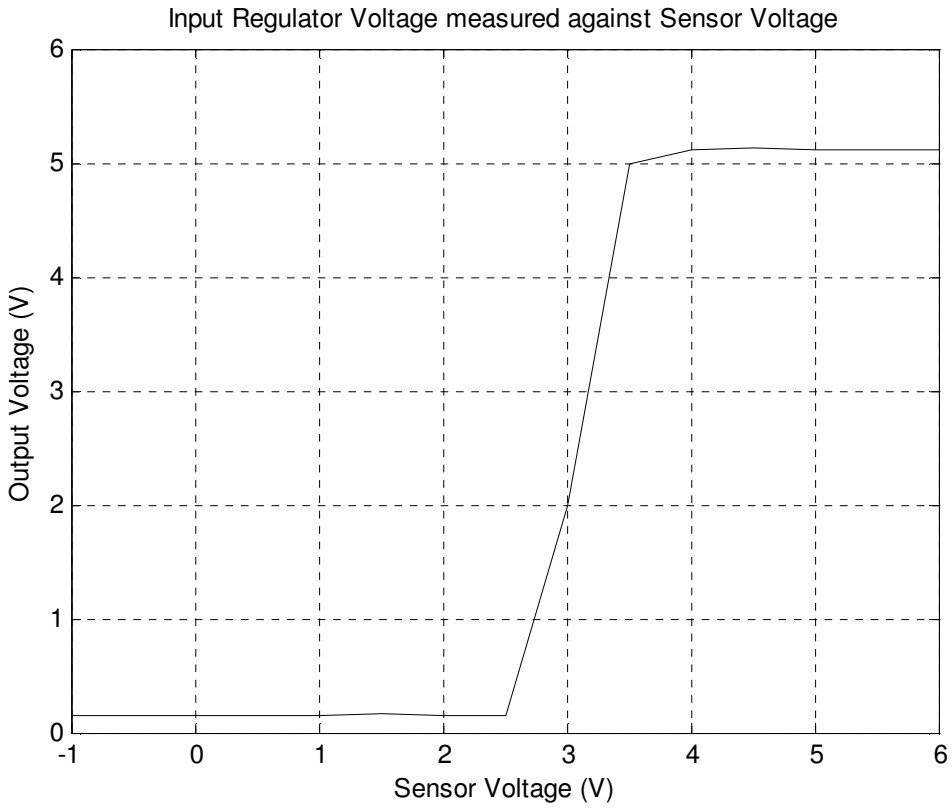

Figure 5.1: Input Regulator Voltage measured against Sensor Voltage; Sensor voltage is on the x-axis; Output voltage is on the y-axis; Output is measured at every 0.5V increment of the sensor

Tabular version of the date in Figure 5.1 can be seen in Table A.1 of the Appendix section A.3. The reason the output of the input regulator is not a perfect step function is due to the fact at threshold the comparator will output 0V instead of V_{CC} or V_{EE} and this results in a value of 2.5V at the output.

5.2 Results of the Force to Visual Feedback System

The force to visual feedback system was designed in the previous chapter to be a simple voltage divider that would take a force sensor which acts as a variable resistor in parallel with a resistor value that has a median value of the sensor range.

The variable resistor was measured to have a range of 12kΩ to 17MΩ with a resistance with a medium pressure to be in the 110k to 120kΩ which is why a resistor

value of 100kΩ was selected. The pressure sensor was mounted onto the frame of the middle finger since this was the finger that would be tightest during grasping of an object. When pressure was at its lowest, the sensor resistance range was highest and the output was 0.03V which was not enough to turn the LED on. As the pressure grew the sensor resistance dropped and the output voltage grows until 4.46V at its maximum. The maximum intensity emitted from the LED came when the output voltage of the circuit was 4.46V. The sensor would output a drop in resistance between these two extremes linearly although without knowing how much force the sensor was actually experiencing there is no way to quantify this relationship.

The force to visual feedback did accomplish the goal of allowing the user to have a qualitative idea of how much force was pushing on the sensor on the middle finger. There was no quantitative force value, but this is overcome due to the fact that we do not have a quantitative understanding of force when we use biological limbs either. Force is measured in our brains as relative values and through long repetition; we know how much force to apply to certain situations. The user of the bionic hand will have to adapt to a new qualitative scheme just as real biological hand would have to, instead of relating pressures with one another, they will have to relate light intensity.

The pressure sensors that were purchased were a thin sensor within a polymer coating. The sensor itself measured only 0.5cm in diameter so this allowed it to be placed on the tip of the finger with relative ease. The problem of using such a thin sensor became apparent when shearing forces of the wires were introduced. Long wires had to feed the circuit board to the tip of the bionic hand. The weight of the wires caused the sensors to try and shear, which resulted in the thin polymer coating to become loose and eventually break off. This was an issue for three out of the four sensors, so only one was mounted onto the frame. If more sensors were able to mount onto the frame, they could all connect into the microcontroller for processing. In the case of the hand grasping on object, the microcontroller would have averaged the results together and shown the intensity on one LED. If the user selected the hand to have a point position, then the microcontroller could have only selected the sensor on the middle finger. This would require additional programming since the program designed earlier took into account the fact that only one force sensor was used instead of all four. The microcontroller would

also have to be adjusted to be able to accept a certain number of analog inputs, one for each sensor being used.

5.3 Results of Amplification Stage

The amplification stage was a non-inverting amplifier that was used on each output line as designed in the previous chapter. Its goal was to drive up the 5V output pulse from the microcontroller to 7.5V with enough current to rotate the motors. When measuring the output after amplification, each non-inverting amplifier had a voltage of 7.24V, giving an error of 3.4%. This error is negligible since the motors only needed to rotate without the need to worry about the rotational velocity. The current after amplification was enough to turn each motor which was simply tested by programming the microcontroller to send a one second pulse to the amplifier which is then connected the motor. Since the motors rotated we can safely say the amplification stage accomplished its goal.

The use of large motors that required such demanding power supply greatly affected this stage and the overall performance of the bionic hand. If smaller less power demanding motors were to be used, the design could have been done differently. The need for high power operational amplifiers might not have been needed which would have reduced the cost by using standard ones instead.

A second benefit to have used smaller motors would be a reduction in power consumption of the circuits needed to drive the motors. Instead of using operational amplifiers, a common-emitter and common-collected cascade amplifier could have been used if the power required was not as great as needed for the current motors. Figure 5.2 below shows the use of a dual-stage amplifier using smaller BJT transistors rather than ideal operational amplifiers.

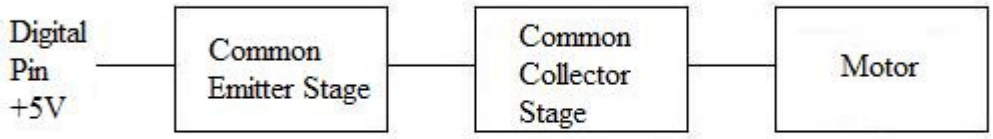

Figure 5.2: Use of CE-CC stage with a smaller motor for more efficient power consumption

The output effectors of the project greatly limited the scope and hindered the objectives. Large motors and muscle wire had many undesirable affects which the next section gives a discussion of the results of the bionic hand as an entire unit.

5.4 Results and Discussion of the Bionic Hand as One Unit

The results of the bionic hand need to account for the motion of the fingers, consistency of their placement, and whether or not the positions of the hand reached the objectives of giving users motor control for everyday activities.

We begin the discussion of the bionic hand as one unit with regard to the motion of the fingers. The motion of the fingers is the ability of the fingers to move in response to a user controlled input to the system. The user wears the control glove which controls the system. When the user flexes their real index finger, the bionic hand is set into the point position. When the user flexes their middle finger, the bionic hand is set into the grasp position. Lastly when both the index and middle fingers are flexed the hand is set into the pinch position. Since each of the fingers on the bionic hand has a different flexion and extension time, each finger must have that pulse sent separately and thus must move one at a time. From the open position, the bionic can move into the point, grasp, and pinch positions. The results are not always consistent and depend a great deal on the tension in the strings. However the system can respond to the user control and set the bionic hand into these three positions. The reverse holds true as well, when the bionic hand is set either into grasp, point, or pinch, when the user releases the control the hand will move back to the open position.

Motion of the hand becomes tricky when trying to move from grasp, point, or pinch to a non-open position. The issue arises from the fact that the control glove must switch between two flexed fingers quick enough for the microcontroller to read the inputs. That is, if the user wanted to move from the point position to the grasp position, the control unit would already have the index finger flexed. The user would have to move from their indexed finger being flexed to only their middle finger being flexed. Unless these happen instantly, the microcontroller will misread the input. If the index finger is taken away from flexion before the microcontroller reads the middle finger being flexed, it will think the user wants to move to the open position again. If the middle finger is flexed before the index finger is released, the microcontroller will read that both sensors are on and set the bionic hand into pinch (the position controlled by both of the control fingers being flexed at the same time).

To compensate this error, the microcontroller would have to be reprogrammed to not read inputs continuously. If there was a delay between reading inputs then theoretically there should be enough time for the user to set their control hand accordingly. Another workaround to this error would be to hold the hand in its current position so that regardless of the control unit, the bionic hand will not move. This would allow the user to set their control and release hold. This way the microcontroller will immediately pick up the new input without any errors.

Consistency was another issue. Using timed pulses works only if the fingers flex the same way each and every time they have to move. This is an ideal situation that cannot exist in real life. The use of strings meant that the tension in the strings ultimately decided how much to flex or extend each finger on the bionic hand. If the string was very tight, when the motor rotated it would move the finger more than if that same string were loose in another situation. Every time there is a slight error in flexion or extension there is no way to compensate this error. The errors just compound on one another which is a problem because eventually each position will be so distorted and not even resemble what it should be. The best case it to look at the open position. When the errors begin to compound, the fingers on the bionic hand extend differently since they are only being timed to extend for so long. Eventually the open position becomes distorted. Through

experimental trials, it was determined that after three positions the hand had considerable error and would not operate according to its theoretical nature.

Figure 5.3 below shows the open position when it's correct, and the open position after the bionic hand has been used several positions. We can see that the fingers are no longer in the correct positions in relation to one another.

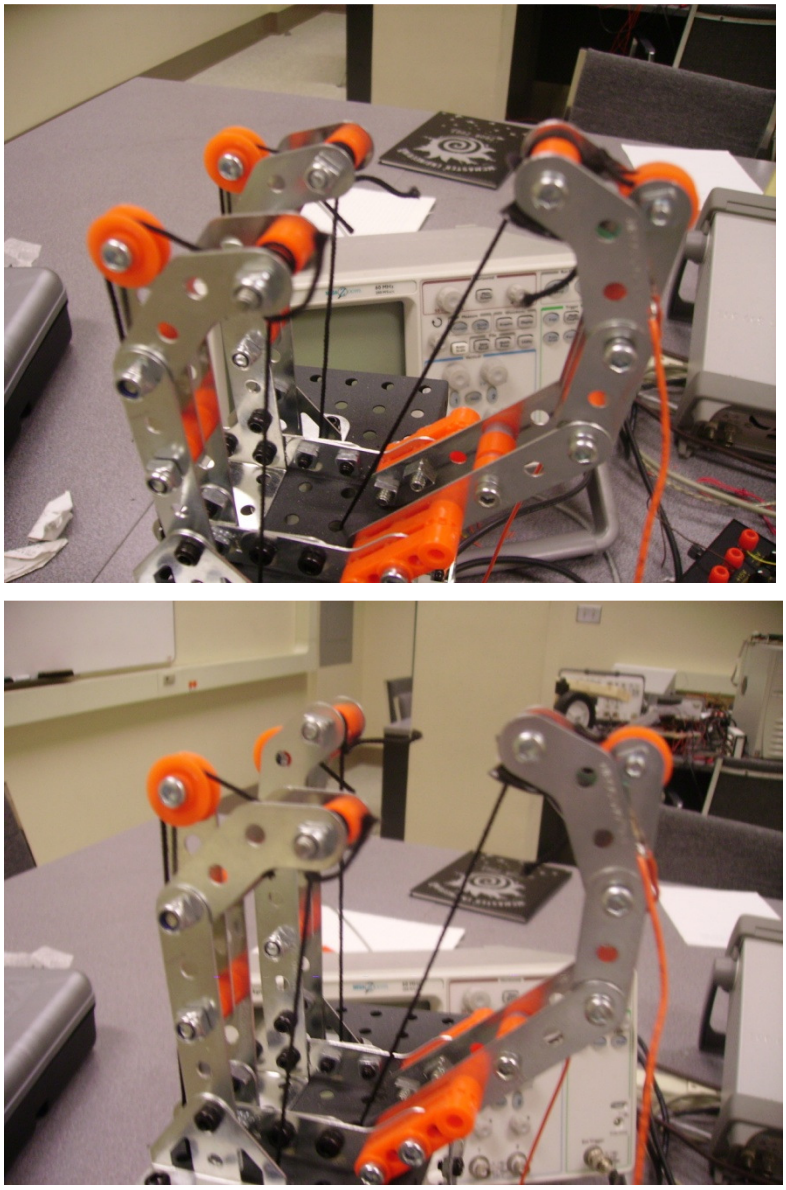

Figure 5.3: Top image shows the open position before use; Bottom picture shows the open position after several runs; Notice the fingers do not realign properly.

As mentioned in the methodology, to compensate error there would need to be sensors in place on the actual joints of the bionic hand that could give feedback as to the position or angle of the joint. Using an error reducing PD controller would mean that we could run the output pulse until the error of the current position relative to a desired result, would converge to zero. This would give results that would not compound errors over time and achieve greater functionality of the bionic hand as a whole, the only issue was that this controller was not known and needed a great deal of prior knowledge using proportional derivative controllers was needed.

The final discussion of the bionic hand as a whole is to see whether or not the positions we set achieved the objective set fourth at the start of the project. Due to the bulky nature of the apparatus and the volume of wires, it was difficult to move the bionic hand and meant that it needed to be stationary. The ability to grasp objects was difficult because the tight strings on the inner part of the joint meant the joint fingers could not closely keep an object tight. If these strings were to be moved, then the bionic hand would be able to grasp and hold onto objects. The contraction force was considerable enough that it would certainly be able to hold an object. The point position was an acceptable result since one of the fingers stood in place, and the sturdiness of the bionic hand allowed force to be pushed on the tip of the finger without any bending as expected, for example when pushing a button.

A possible solution would be to actuate the joints themselves without pulleys or strings as this would allow the bionic hand to be less bulky and grasp objects easier. The next and final chapter gives a conclusion of this project given the objectives we set and a description of where this project would head if it was to be continued and have more work invested on it.

Chapter 6
Conclusions and Recommendations

This final chapter gives a concise conclusion of the project related to the stated objectives in the introductory chapter. Conclusions are based off the results obtained and their critical discussions. The areas to be considered are the control unit, bionic hand, and also the four major stages developed for the system designed in this report. Finally future recommendations are given in a manner of improvements to the overall design of the bionic hand and where we would have taken this project given a larger scope.

6.1 Conclusions of the Designed Stages

In the objectives, it was stated that the primary goal of this project was to give users motor control and limited sensory feedback with an easy to use interface system. The control unit would have to integrate with a system that can run the bionic and as well as receive feedback.

The control unit achieved the task of allowing users to have an easy to use interface that did not require any invasiveness or any electrodes. The user could simply wear a glove which did not hinder the performance of their biological hand in any way since the sensors were placed on the back. When the user wanted to set the bionic hand into a certain position, they just need to combine their index and middle finger and flex them. The requirements of the system that operated the bionic hand were that they needed to accept user controlled input and move the bionic hand as necessary.

The input regulator allowed the user controlled input signals via the Hall Sensor to enter a microcontroller with a binary input range of 5V and 0V depending on the position of the magnet and if it was over or under a certain distance threshold. The design gave a relative error of 2.4% which is acceptable. Current isolation was another key factor that was achieved. Current from the sensors cannot enter the microcontroller, nor

in the other direction due to the input regulator stage isolating the two. The safety requirement of this project was therefore met.

The microcontroller's objectives were to accept user controlled input and output the positions of the bionic hand. Depending on the position these results were achieved only when moving from the open position or moving to the position. The design objective that wanted to remove this intermediate condition was not met because the inputs were too sensitive to the user's control glove. Two workarounds were given in the discussion which included adding a delay in the microcontroller program or by having a hold button placed on the control glove. These two solutions would allow the bionic hand to move from a non open position to another non open position.

The amplification stage was a simply stage that just needed to drive the motors under the control of the output digital pins on the microcontroller. The output control was amplified to 7.5V with enough current to control the motors. Directional control was also achieved by using dual amplifiers on the motor lines. Power dissipation was very large using the high powered 1A output operational amplifiers which means that a very strong power supply is needed for this project. Smaller, less power demanding output effectors would be needed to reduce the overall power consumption and allow more portability. In order to run all the circuitry and motors we needed a power supply of +/- 9V using an AC to DC converted straight from a power line. This affected the portability of the entire unit along with several other important factors. The other factors that affected portability were the design of the bionic hand that the apparatus that was constructed and the fact that wires needed to run from the control glove to the circuitry, from the circuitry the motors, and finally from the motors to the joints.

The objectives for limited sensory feedback were achieved using a force to visual mechanism that would convert how much pressure or force a piezoelectric sensor was experiencing to a voltage signal capable of driving an LED. The qualitative relationship was that more force meant more light intensity and vice versa. This allowed us to close the bionic hand on an object which would then give sensory information back to the user. Since only one force sensor was used due to the fragile nature of them, the one sensor was mounted onto the middle finger of the bionic hand as this was used for the point position and also the grasp position.

Lastly, the bionic hand as one unit had variable results depending on how many times it had been running. The use of strings gave non consistent results which meant the timing pulses would compound error and the positions eventually became distorted. Since the motion of the fingers will never be ideal we would have to use an error compensation controller which would require additional sensors on the joints and the use of a negative feedback controller. The ability to grasp objects was the final objective given in the introduction and due to the bulky apparatus and wired components it was difficult to move the bionic hand. This meant it had a large problem in grasping objects unless they were placed within the hand.

Given the errors that occurred, the project nevertheless achieved many of its stated objectives and gave us a very good understanding of the complexity involved in designing prosthetic devices. Our bionic hand was a proof of concept that a very easy to use, non invasive method could operate a prosthetic device. The control systems add a large amount of complexity to the operation of prosthetic devices. The control system developed in this report did achieve the fact had motor control over the bionic hand. Improvements to the design process are described in the future recommendations section below.

6.2 Future Recommendations

If this project was to continue to be worked on, there would have to be alternative methods of output and sensory information as well as a new designed apparatus. Smaller motors would be used with less power consumption as this would allow for more portability of the hand. The apparatus could then be designed to be smaller and less hindered. A smaller base apparatus would allow the hand to move and not have to be held stationary when testing.

The second part of making a more portable project would be to remove the wired components and send the control inputs to the microcontroller wirelessly. This would achieve isolation of currents which was a task of the input regulator. This would allow the user to move their control glove with no problem of worrying about hindering the bionic hand. A wireless component would have added a greater ease of use as well as current

isolation and would be a next step towards continuing the work of this project in the future.

In the form of sensory feedback, more sensors would ideally be placed on the frame of the hand to allow greater force or pressure analysis. More sensors would give the user a greater degree of information and allow them to have more sensory feedback for a greater number of tasks. In addition, thermocouples could be added to the bionic hand and an electrode placed on the user that would let the user feel the effects of temperature minus extreme hot and cold situations. The more sensory information we can give back to the user, the better the overall performance and the closer we can be at restoring the functions the user has lost.

The last thing that would have changed comes in the design process. Given the knowledge we know now on controller systems for robotic devices, it would make sense to have used a desired trajectory in addition to error compensation. This can be added onto the existing design or even small sensors build onto a new apparatus with the above corrections. This would eliminate many of the errors associated to the motor control.

All together, we feel the project was a success in the sense it gave us an understanding of the deign process involved, and many objectives were met. The recommendations listed above would only enhance the project and give us an even further appreciation of the work that needs to be involved into restoring motor and sensory functions to users.

Appendix A

A.1: Resistor Relationships for the Input Regulator

Resistors R1 and R2 control the voltage threshold for the comparator. The threshold voltage was set to be 3V, so using voltage division the following relate R1 and R2:

$$9\text{V} \times \frac{\text{R2}}{\text{R1} + \text{R2}} = 3\text{V}$$

$$\frac{\text{R2}}{\text{R1} + \text{R2}} = \frac{1}{3}$$

$$\text{R1} = 2 \times \text{R2}$$

R1 must be twice the value of R2, so standardizing these values we simply use R1 = 20kΩ and R2 = 10kΩ.

Resistors R3 and R4 are used for the inverting amplifier. To find the resistor relationship, the output relative to the input must be solved on an inverting amplifier assuming ideal conditions, which we know that the attenuation factor a, must be equal to 0.2778. Starting with the inverting amplifier, using a nodal equation at the non inverting port:

$$\frac{0 - \text{Vo}}{\text{R4}} + \frac{0 - \text{Vs}}{\text{R3}} = 0$$

$$\frac{\text{Vo}}{\text{Vs}} = \frac{-\text{R4}}{\text{R3}}$$

$$0.2778 = \frac{-\text{R4}}{\text{R3}}$$

Standardizing these values leads use to choose R3 = 100kΩ and R4 = 33kΩ. This yields an acceptable result.

Lastly we follow the same process for resistors R1 and R2 when finding the constant voltage division for b = -2.5V via R5 and R6. Using the negative V_{EE} supply we yield:

$$-9\text{V} \times \frac{\text{R5}}{\text{R5} + \text{R6}} = -2.5\text{V}$$

$$\text{R5} + \text{R6} = 3.6 \times \text{R6}$$

$$R5 = 2.6 \times R6$$

Standardizing these values we obtain R5 = 22kΩ and R6 = 10kΩ that yield an acceptable result.

A.2 Output Voltage from a Piezoelectric Sensor

From Figure 3.3 we can develop the following equations:

$$is = iR + iC$$

$$is - iR = iC$$

$$is - iR = C\frac{dVo}{dt} = K\frac{dx}{dt} + \frac{Vo}{R}$$

Transforming this into the frequency domain using a Fourier Transform, we obtain:

$$\frac{Vo(jw)}{Vs(jw)} = \frac{KsjwT}{jwT + 1}$$

Where T is the time constant RC. This behaves as a high pass filter since when the angular frequency w is high, the output is unity.

A.3 Tabular Results from the Input Regulator

The graphical data in Figure 5.1 has its values summarized in Table A.1 below.

Sensor Voltage (V)	Output Voltage (V)	Sensor Voltage (V)	Output Voltage (V)
-1.0	0.153	3.0	5.0
0	0.154	3.5	5.12
0.5	0.152	4.0	5.14
1.0	0.153	4.5	5.12
1.5	0.153	5.0	5.12
2.0	0.158	5.5	5.12
2.5	0.152	6.0	5.12

Appendix B

Microcontroller Code

```
/* EE 4BI6 - Biomedical Capstone Project

  Evan McNabb
  Chris Kidd

  Design of a non-invasive Human Computer Interface (HCI)
  to control a bionic hand. This program is loaded onto the microcontroller
  and as of Jan 12 2009:
    Accepts 2 inputs from magnet sensors: inputPin1, inputPin2
    Produces 4 outputs: outputPin1 - outputPin4

*/

/* Function Prototypes */
void newPosition(int position, int current);

/* Pin Variables */
int inPin1 = 11;
int inPin2 = 12;

int outPin1_1 = 2;
int outPin1_2 = 3;
int outPin2_1 = 4;
int outPin2_2 = 5;
int outPin3_1 = 6;
int outPin3_2 = 7;

/* Local Variables */
int input1;
int input2;
int current = 1;
int position;

int T = 1500; // Base time that all flexion and extension can be based off of

/* Function: setup()
   Purpose:  The purpose of this function is setup the pin variables to either be input or
```

```
output depending on thier nature
        Also inializes some local variables before the main loop
*/
void setup()
{
  pinMode(inPin1, INPUT);
  pinMode(inPin2, INPUT);
  pinMode(outPin1_1, OUTPUT);
  pinMode(outPin1_2, OUTPUT);
  pinMode(outPin2_1, OUTPUT);
  pinMode(outPin2_2, OUTPUT);
  pinMode(outPin3_1, OUTPUT);
  pinMode(outPin3_2, OUTPUT);
}

void loop()
{
  /* Read inputs from Input Regulator */
  input1 = digitalRead(inPin1);
  input2 = digitalRead(inPin2);

  /* Decode inputs and choose the correct hand position */
  if(input1 == LOW && input2 == LOW) {
    position = 1;
  }
  else if(input1 == LOW && input2 == HIGH) {
    position = 2;
  }
  else if(input1 == HIGH && input2 == LOW) {
    position = 3;
  }
  else if(input1 == HIGH && input2 == HIGH) {
    position = 4;
  }

  /* Check to see if the current position being read is the previous */
  if(current != position) {
    newPosition(position, current);    // Move the hand relative to the current position
    current = position;                // Set the current position to the new postion
  }
}

/* Function to move motors from their current position to the new position */
void newPosition(int position, int current) {

  /* Position 1 implies open
```

```
   Position 2 is closed
   Position 3 is point
   Position 4 is pinch
*/

/* Move from open to closed */
if(current == 1 && position == 2) {
  digitalWrite(outPin1_1, HIGH);
  digitalWrite(outPin1_2, LOW);
  delay(1.2*T);
  digitalWrite(outPin1_1, LOW);
  digitalWrite(outPin1_2, LOW);

  digitalWrite(outPin2_1, HIGH);
  digitalWrite(outPin2_2, LOW);
  delay(0.3*T);
  digitalWrite(outPin2_1, LOW);
  digitalWrite(outPin2_2, LOW);

  digitalWrite(outPin3_1, HIGH);
  digitalWrite(outPin3_2, LOW);
  delay(0.7*T);
  digitalWrite(outPin3_1, LOW);
  digitalWrite(outPin3_2, LOW);
}

/* Move from closed to open */
if(current == 2 && position == 1) {
  digitalWrite(outPin1_1, LOW);
  digitalWrite(outPin1_2, HIGH);
  delay(2.2*T);
  digitalWrite(outPin1_1, LOW);
  digitalWrite(outPin1_2, LOW);

  digitalWrite(outPin2_1, LOW);
  digitalWrite(outPin2_2, HIGH);
  delay(0.8*T);
  digitalWrite(outPin2_1, LOW);
  digitalWrite(outPin2_2, LOW);

  digitalWrite(outPin3_1, LOW);
  digitalWrite(outPin3_2, HIGH);
  delay(0.9*T);
  digitalWrite(outPin3_1, LOW);
  digitalWrite(outPin3_2, LOW);
}
```

```
/* Move from open to point */
if(current == 1 && position == 3) {
  digitalWrite(outPin2_1, HIGH);
  digitalWrite(outPin2_2, LOW);
  delay(0.3*T);
  digitalWrite(outPin2_1, LOW);
  digitalWrite(outPin2_2, LOW);

  digitalWrite(outPin3_1, HIGH);
  digitalWrite(outPin3_2, LOW);
  delay(0.7*T);
  digitalWrite(outPin3_1, LOW);
  digitalWrite(outPin3_2, LOW);
}

/* Move from point to open */
if(current == 3 && position == 1) {
  digitalWrite(outPin2_1, LOW);
  digitalWrite(outPin2_2, HIGH);
  delay(0.8*T);
  digitalWrite(outPin2_1, LOW);
  digitalWrite(outPin2_2, LOW);

  digitalWrite(outPin3_1, LOW);
  digitalWrite(outPin3_2, HIGH);
  delay(0.9*T);
  digitalWrite(outPin3_1, LOW);
  digitalWrite(outPin3_2, LOW);
}

/* Move from closed to point */
if(current == 2 && position == 3) {
  digitalWrite(outPin1_1, LOW);
  digitalWrite(outPin1_2, HIGH);
  delay(2.2*T);
  digitalWrite(outPin1_1, LOW);
  digitalWrite(outPin1_2, LOW);
}

/* Moved from point to close */
if(current == 3 && position == 2) {
  digitalWrite(outPin1_1, HIGH);
  digitalWrite(outPin1_1, LOW);
  delay(1.2*T);
  digitalWrite(outPin1_1, LOW);
```

```
  digitalWrite(outPin1_2, LOW);
}

/* Move from open to pinch */
if(current == 1 && position == 4) {
  digitalWrite(outPin1_1, HIGH);    // Flex the middle finger
  digitalWrite(outPin1_2, LOW);
  delay(1.2*T);
  digitalWrite(outPin1_1, LOW);
  digitalWrite(outPin1_2, LOW);

  digitalWrite(outPin2_1, HIGH);    // Flex the left index finger
  digitalWrite(outPin2_2, LOW);
  delay(0.3*T);
  digitalWrite(outPin2_1, LOW);
  digitalWrite(outPin2_2, LOW);
}

/* Move from pinch to open */
if(current == 4 && position == 1) {
  digitalWrite(outPin1_1, LOW);    // Extend the middle finger
  digitalWrite(outPin1_2, HIGH);
  delay(2.2*T);
  digitalWrite(outPin1_1, LOW);
  digitalWrite(outPin1_2, LOW);

  digitalWrite(outPin2_1, LOW);    // Extend the left index finger
  digitalWrite(outPin2_2, HIGH);
  delay(0.8*T);
  digitalWrite(outPin2_1, LOW);
  digitalWrite(outPin2_2, LOW);
}

/* Move from closed to pinch */
if(current = 2 && position == 4) {
  digitalWrite(outPin3_1, LOW);    // Extend the right index finger
  digitalWrite(outPin3_2, HIGH);
  delay(0.7*T);
  digitalWrite(outPin3_1, LOW);
  digitalWrite(outPin3_2, LOW);
}

/* Move from pinch to closed */
if(current == 4 && position == 2) {
  digitalWrite(outPin3_1, HIGH);    // Flex the right index finger
  digitalWrite(outPin3_2, LOW);
```

```
    delay(0.9*T);
    digitalWrite(outPin3_1, LOW);
    digitalWrite(outPin3_2, LOW);
  }

  /* Move from point to pinch */
  if(current == 3 && position == 4) {
    digitalWrite(outPin1_1, HIGH);    // Flex the middle finger
    digitalWrite(outPin1_2, LOW);
    delay(1.2*T);
    digitalWrite(outPin1_1, LOW);
    digitalWrite(outPin1_2, LOW);

    digitalWrite(outPin3_1, LOW);    // Extend the right index finger
    digitalWrite(outPin3_2, HIGH);
    delay(0.7*T);
    digitalWrite(outPin3_1, LOW);
    digitalWrite(outPin3_2, LOW);
  }

  /* Move from pinch to point */
  if(current == 4 && position == 3) {
    digitalWrite(outPin1_1, LOW);    // Extend the middle finger
    digitalWrite(outPin1_2, HIGH);
    delay(1.2*T);
    digitalWrite(outPin1_1, LOW);
    digitalWrite(outPin1_2, LOW);

    digitalWrite(outPin3_1, HIGH);    // Flex the right index finger
    digitalWrite(outPin3_2, LOW);
    delay(0.7*T);
    digitalWrite(outPin3_1, LOW);
    digitalWrite(outPin3_2, LOW);
  }
}
```

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