Design and control of a three finger dexterous prosthetic

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by
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This paper describes the development of an upper limb, closed loop, dexterous prosthetic device. All parts of the design of the hand are investigated from hand design, finger actuation, sensor design to the control system. Finger position control is realized using pulse width modulation, pressure sensor feedback, torque monitoring and microcontroller control.
Introduction

It has happened to my friends and family. It must be hard to cope with the loss of a limb. Some people are unfortunately born without certain limbs. Not to trivialize one limb over the other, but losing an upper limb is more traumatic than losing a lower limb. A lower limb prosthetic can be made to be less noticeable. Long pants, socks and shoes are available to make the amputee feel more comfortable about his prosthetic. Balance and walking are two functions which are the mostly widely used functions of the foot and leg. The foot is otherwise used more for power than to manipulate delicate objects and it is easier for the amputee to adapt.

On the other hand, an upper limb is a multifunction, high visibility device which is extremely difficult for man to efficiently replicate. The hand, as it is well known, is the most complicated part of the body. It consists of 25 bones, a host of ligaments and muscles as well as many highly adaptive sensors. The complexity, weight and alignment of these components make it, at this writing, impossible for man to duplicate with any usefulness. Maybe that is why so many people have developed many different hand designs. The more complicated the hand design, the more sensors needed to determine digit position, temperature, pressure, etc. which
inherently will increase the need for data processing.

Clinically available prosthetic devices are limited in their appeal. There are a couple of designs available depending on the usage. 99% of the prosthetic devices are of a "gripper" design consisting of one motor driving 2 fingers and an opposing thumb in a gripper type action. People who are concerned about cosmetics can have 4 fingers and a thumb with a rubber "skin" over the gripper. These devices are myotically controlled with the simplest ones being ON/OFF controlled and the more complicated controllers being ON/OFF and with variable speed. These open loop controllers require the person to visually observe the prosthetic device as it opens and closes so as not to crush the intended object. There has been work done with sensory substitution in an attempt to make a feedback circuit for the user. While some results seem promising, this method is not a true solution for the feedback problem.

An upper limb prosthetic device can be divided into three general yet distinct parts. These are the hand, biological interface unit and a control package which bridges biological and electronic control signals and voltage levels. The biological interface unit is a term that I loosely defined to identify either the myotic or neurotic interface with the body's electrical signals. Myotic control uses residual muscle contractions in the stump to generate a signal and neurotic control uses neural signals generated from the bodies
nervous system. The bridging control package is there to filter out the required signals from the background noise and convert them to appropriate levels (e.g. 5 volts full scale). The control package would also convert sensor feedback to biological levels and transmit them to the biological interface unit.

This paper concentrates on developing a control system for a hand that has three fingers with independent contractile motion. Incorporated in these fingers will be pressure sensor feedback so as to limit the amount of applied pressure. Even though the bulk of the project will be in the design of the control system, there are other tertiary components. Some other considerations are hand design, finger motion generation/linkage and sensor construction.
Goals

The ultimate goal of this thesis has been to design and build a upper limb closed loop prosthetic hand capable of being controlled neurally. At first, this seemed to be a noble goal but upon further investigation, the amount of work required would have been enough for 2 PhD candidates. Therefore, the scope of the project was reduced to include only the development of a three finger hand controlled by a microprocessor. The test chosen to assess functionality of the hand developed was to grab an egg without breaking the shell.

Presently, one drawback of market available prosthetic devices is the "mechanical" motion when it is used. This unnatural movement is exemplified when grasping objects and even shaking hands and the prosthetic looks and feels clumsy or mechanical. The mechanical motion is partially due to the linkage of the fingers and the control systems. These hands built today are mostly designed with two fingers and an opposing thumb. This minimum number of fingers allows simple construction of the hand and controller as well as a more dependable operation. But, the actuation of the fingers is through direct mechanical linkage to all the fingers so that the fingers flex and extend at the same time and usually the same rate. The end result is a pincher type movement much
like the ones robots use to grab objects from the ocean floor. This layout of fingers creates an awkward situation when grabbing all but the most regularly shaped objects. For instance, it is not uncommon for an amputee, when opening jars, to not hold the jar with the robotic fingers. Instead, they will use the prosthetic forearm as a lever and clamp the jar to the body to hold it and use the "good" hand to twist the top off. This one example shows how the awkward motion of the prosthetic limits its function.

The thesis therefore is intended to improve on this situation by making a hand that has independent movement of all three fingers in a closed loop situation. Modern prosthetics as described above, have fingers with only one degree of freedom (D.O.F.). My design will have fingers that will have two D.O.F. and a thumb that also has two D.O.F. Advanced robotic hand designs, like UTAH/MIT\(^1\) or Stanford/JPL\(^2\), have fingers and thumb that will each have four D.O.F. Such hands could not be used as prosthetic hands because the motors or other form of actuation for the hand would make it prohibitively large and heavy.

Controls for commercially available hands are rudimentary mostly due to the type of actuation. Today's prosthetic devices are myoelectrically (muscle activated) controlled. Residual muscles left in the stump are contracted which in turn generate an electrical signal. These signals are picked up by skin mounted sensors and after some signal processing,
control the fingers. More advanced controllers allow the motor to contract with variable speeds. The reason for the limited control possibilities is the limited number of muscles on which to place the myoelectrical sensors. The myoelectric sensors rely on contraction of the muscles which produces a localized voltage of around 10mV that during intense contraction can reach as much as 30mV. It should be noted that different size muscles will generate different voltage levels.

Neural controlled prosthetics have not made it out of the lab due to two major reasons: the neural signal strength and nerve locations. First, the neural signal of interest is about 50uV-500uV \(^5\) which is on the same order of the incident noise. With the noise and signal strength about the same magnitude, filter and amplifier design are critical components. Since the signal strength is so low, any introduction of additional noise will swamp out the neural signal. Therefore, the filters and amplifiers designed are being built on the sensor using a combination of VLSI and micromachining techniques \(^4,5\).

Since the nerves are located farther inside the body, the sensors must be located inside the body. BeMent et al \(^5\) and others have successfully designed and developed microelectronic sensors for in vitro use. They have produced limited success although many other challenges must be met before these sensors can be used in a real life prosthetic.
Some of these problems include sensor positioning, body rejection of implants and lead wire sealing. For example, there is a problem with the baseline voltage random wandering which is due to the electrode/electrochemical interface. Voltage drift due to this can be ± 50 mv which is 100 to 1000 times the neural signal.
Hand Design

When speaking of prosthetics and robotics, the definition of a hand is the physical hand, controller and the "forearm" which usually houses the motors. Years from now, a goal would be to develop a five fingered hand with 4 degrees of freedom per finger which is light weight, powerful and mounted in a small package. Other universities have built such robotic hands and it would be futile for me to do the same. Examples of such hands are the UTAH/MIT and the Anthrobot. But such hands have innate problems which make them impractical for prosthetic use. One such problem is that the hands are just too heavy mostly due to their actuators. The Utah/MIT and Anthrobot hands were designed at different times and for different purposes, but they have similar properties which I would like to illustrate. There are three major problems with these hands which exclude them from being used as prosthetic hands. They are size, weight and the means of controlling the hand.

First to be considered is the physical size of the hand. Both hands are designed to have hands that are relatively anatomically accurate although the Anthrobot has a better design. The "forearm" sections of these hands are too large and do not permit easy affixation to the body. For example, the Anthrobot has a forearm which is 4" by 6" and 1 1/2 times as long as the typical human forearm. Since a prosthetic device
should look as much like its human counterpart as possible, this construction would be much too large.

The second problem is their weight which can be directly attributed to the complexity of the hand itself. Since each of these fingers has 4 DOF, each finger will have a minimum of 4 motors driving it. Space age materials can be used to reduce the size and weight of the frame and fingers. But, the DC motors still utilize permanent magnet motors and the more powerful motors use still heavier rare earth magnets.

The final problem with these hands is the type of controller required to operate them. These hands make use of multiple feedback sensing using sensors such as like Hall Effect, optoelectric pressure and tension sensors to accurately determine the location of the fingers in space. These sensors produce a plethora of data which needs to be assimilated by the controller. For both of these hands, this translates into computer controlled. The amount of data and controller power required are directly proportional to each other so the more data needed to be examined, the more powerful the controller needs to be. If a neural sensor were used, most of the data would be fed back to the body and the controller would be smaller. Some data from these hands would be frivolous on a prosthetic. For example, the Hall effect devices in the Utah/MIT hand measure finger angle. These are unnecessary since the person can look to see his finger angle.

Do not misunderstand me, it would be nice to incorporate
these qualities into a modern day prosthetic device but it is just not possible. Both of the above mentioned hands are excellent but just not practical because they are too complicated. The major limiting factor is the size and weight of the motors necessary to drive the fingers. I investigated alternatives to motors but they proved insufficient for the load required. This shall be discussed later.

On the other end of the spectrum are the modern day, clinically available prosthetic myoelectrically controlled hands. These types of hands are available with cosmetically different looks but with functionally similarly construction. Hand types are generally designed using a two finger pincher type or a three finger hand design previously described. In effect, the hands employ a pincher type end effector driven by a single DC gearmotor. When the user wants to open or close the hand, he flexes muscles in his stump to control the motor. The motor, being linked directly to all the fingers, then drives both the fingers and the opposing thumb. Therefore, the fingers and thumb flex and extend at the same speed. This is a proven and time tested design which produces reliable results that is simple for the user. These hands have 2 DOF, one for the thumb and the other for the opposing fingers. One reason that more degrees of freedom have not been attempted is the difficulty in isolating muscle responses in the stump to control these other degrees of freedom. A method which allows closer sensing of myotic signals will increase the DOF in the
hand or allow individual finger motion.

Actuation

A tertiary goal of the project was to design a hand that has a greater DOF than is clinically available that still can be easily controlled. Each of finger has 2 DOF and each finger is individually driven for a total of 6 DOF. The principle actuation method employed is 12 V DC gear motors driving jacket wrapped cables. Other actuation methods are available but either add too much weight or are difficult to incorporate into such a confined space as a hand dictates.

One other method investigated was a product called "Muscle Wire". Muscle Wire is a form of memory shape material. Memory shape materials are usually metals that can be distorted into any shape but with the addition of a catalyst (e.g. water), they will return to their original shape. In the case of Muscle wire, the catalyst is heat. Muscle wire, when heated contracts to its original shape and will stay contracted as long as the heat is applied. Heat is produced by sending a current, either AC or DC, through the wire. The amount of contraction depends on the amount of current applied but the maximum is on the order of 3-8% of its unheated length. Using the Muscle wire to this specification will reduce the life span of the material to approximately 100 cycles. Contracting Muscle wire in the 3-5% range increases its life span to a million cycles or so.
While the concept of memory shape materials appears initially attractive, there are several obstacles which have to be worked out. First, the muscle wire is fairly weak. My target goal was to be able to grasp up to a 10 pounds per finger. The muscle wire manufacturer boasts that the wire's maximum recovery force is about 2.5 \text{tons/in}^2. Since the largest wire they offer is 150 um, that turns out to be a force of about two ounces. For a target static load of 10 lb, there would need to have 73 of these wires. The problem is not the physical space required since 73-150 um diameter wires require 2.827x10^3 \text{sq in} to install. The problem is that all 73 wires need to be electrically isolated from each other and each driven individually. While possible, the controller and contacts required for driving the muscle wire would be prohibitively large.

In addition, the isolation requirement would increase the area needed to install the wires three or four times. There are other problems associated with this material which make it unacceptable in this application. These include slow relaxation periods, contraction control difficulties and wire control. When some of these problems can be worked out, this type of memory shape product has a bright future in prosthetic devices as tendon type actuators. When some of these problems are overcome, these wires, which more closely resembles the humans muscle fibers, will replace DC gearmotors as the preferred means of actuation. With the replacement of the
gearmotor, the weight of the limb will decrease which will increase its appeal.

This project makes use of DC motors and more specifically, DC gearmotors. The DC motor was selected because the motor is easily operated using batteries and it is easier to control than AC motors. More specifically, the DC motor used is a permanent magnet motor with the magnet driving the field and motor control is achieved by adjusting the armature current. Separately excited armature and field currents would require more energy to operate and be more complicated to control since both field and armature must be monitored. Gearmotors were used to increase the output torque at the expense of speed. Typically, DC motors of this kind run about 5-6000 rpm in a no-load situation. With any type of direct drive to a motor with these speeds would make control difficult so the reduction in speed is a welcome one. It was determined (see Appendix D) that for the intended design, a minimum of 10 in-lb torque was needed from the motor. Ideally, a small compact motor would be mounted in a forearm type enclosure. But due to budgetary constraints, miniaturized DC gearmotors could not be obtained and standard 12 V permanent magnet gearmotors, Dayton model 2L010, were used. Other characteristics of this motor are listed below. The full load torque appears excessive but under a maximum load conditions (10 lbs), the motor torque necessary is approximately 13.3 in lbs. The physical size of the motors
also eliminate their use in a prosthetic device.

<table>
<thead>
<tr>
<th>Model No.</th>
<th>Full Load RPM</th>
<th>Full Load Torque</th>
<th>Power (HP)</th>
<th>Full Load Amps</th>
<th>Gear Ratio</th>
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<td>2L010</td>
<td>25.0</td>
<td>20 in-lb</td>
<td>1/125</td>
<td>1.3</td>
<td>270:1</td>
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**Hand Construction**

Anatomically, the human thumb is placed to the side of the hand and in the neutral position, at an angle of 45 degrees from the fingers. An example of the thumb's flexibility is displayed when an object is grabbed using the tips of the fingers and with the fingers held straight. The base of the thumb moves even with the base of the fingers. Therefore, the thumb presented a special problem of where to place it and at what angle should it be mounted. If the thumb were mounted at a large angle, small objects would be grabbed incorrectly. Similarly, if the angle were too small, large objects could not be grabbed.

It is not the purpose of this project to replicate the thumb but to give a good approximation. It was therefore decided to place the thumb in the middle between the opposing fingers. This best approximates the thumb's location when it grasps objects. A human thumb tries to align itself in between the opposing fingers to increase stability. To accommodate large objects, the thumb was mounted at a 45 degree angle from the fingers to mimic the human design at
rest. An improvement to this design, which I did not implement, is to give the thumb one more degree of freedom by rotating it around its base. The addition of a rotating thumb would allow the thumb to rotate and grasp smaller objects more naturally. It is in this way that a wide variety of objects could be handled.

All throughout this project, cost was a significant factor so there were two ways of accomplishing goals, the way it should have been done and the way I could afford it to be done. The tendon and its routing are classic examples of this. Tendons were envisioned to be cables sleeved in a jacket so that the combination of the two had a low rubbing friction but with the cable having a high tensile strength. Teflon coated cables and teflon lined jackets would have been ideal for such an application. The cables also had to be easily manipulated since they are wound around pulleys and anchored somewhere on the finger. These cables need to have a tensile strength of about 26-40 lbs depending on the location of the load (see calculations Appendix D). But these cables should be designed to withstand 9x-10x as much. This safety zone limits the effects of stretching and long term cable deterioration.

The jacket is used to allow easier routing of the cables without requiring constant tension and pulleys. The jacket replaces the pulleys and it should have enough strength so as not to compress and dissipate the power delivered from the
motor. On the other extreme, the jacket can not be used to navigate too many corners. The practical limit of jacket bending before the jacket/cable friction exceeds the intended pressure is between 225-270 degrees. Low friction cable assemblies (including jacket and cable) were investigated but alas, the assemblies were either too bulky to work with or the cost was prohibitive. Therefore, both the jacket and cable are nylon. The friction in the assembly was lowered by using a silicone lubricant rubbed onto the cable.

The basic finger construction is the same for both the fingers and the thumb. The hand design used is diagrammed in Appendix B. In addition to structural strength, two functions had to incorporated in the fingers: sensing and tendon routing. Tendons were chosen over mechanical linkage for their light weight and the ease of routing through the finger.

The hand itself was manufactured using oak and white pine woods, plastic pulleys and metal sensors. Ideally, I would have built the hand with aluminum to take advantage of aluminum's high strength, light weight and relatively low cost. Again, due to budgetary constraints, I had to use wood for the bulk of the hand. Using wood increased the size of the fingers since slightly wider components were necessary to keep the structural goals. The hand has to not only be able to withstand the torque of grasping but also be able to accommodate a sensor and cable routing. Oak was selected for the finger members for its strength as compared to pine.
Sensors

One of the key design elements of a prosthetic hand is the accuracy and resolution of the sensors used. There are many different types of sensors which can be used to provide feedback to the controller. Sensors can be grouped into two categories, touch and tactile sensors. Touch sensors are used to detect the presence or lack of contact. A simple example of a touch sensor is a contact switch or even more simply, a switch. A tactile sensor's output is more specific than those of a touch sensor in that they measure the magnitude of a position variable or pressure on the contact surface. Examples of these are joint angle sensors, slip, pressure and temperature sensors.

Since tactile sensors measure the magnitude of the applied pressure, they are most often used sensor type in most robotic and prosthetic hand applications. Tactile sensors also require much more powerful data processing procedures. Nevertheless, tactile sensors are the sensor of choice. Tactile sensors can be broken down into two further sub groups, arrayed and nonarrayed sensors. Arrayed sensors are the more powerful of the tactile sensors since in addition to measuring the magnitude, they also measure the load location with a certain resolution. Nonarrayed sensors only measure the pressure with the resolution depending upon the size of
the sensor.

In actuality, there is no foreseeable method of replicating the sensor capabilities of the human hand. The human hand has many layers of sensors which sense touch, temperature, etc. with a wide dynamic range. All these sensors are cleverly packaged in a flexible, elastic membrane called skin.

According to Leon Harmon of Case Western Reserve University, ideal sensors should have certain properties among them, sensors should be skin like, thin and flexible, highly sensitive, have a fast response, good spatial resolution and a continuously variable output. Examples of these specifications are:\n
Spatial resolution: 1-2mm (.04-.08in)
Response Time: 1-10ms
Sensitivity: 10 mN (.0022lb or 0.036 oz)
Maximum Force: 10 Newtons (2.25 lb or 36 oz)

Design criteria as listed above will be difficult to implement in a prosthetic device. Spatial resolution, the distance between sensor points in an arrayed sensor, of 1-2mm is difficult to manufacture. Capacitive arrays have been found to be the most promising especially the capacitive array designed for the Stanford/JPL. The Stanford/JPL, like some of the other arrayed sensors, make use of a rubber type surface which adds to the feel of the hand. The maximum force of 10 N is small considering the human hand can experience
much more than that. I have investigated two different sensors which I initially thought would work well in a prosthetic device. One of the sensors was based upon a carbon fiber felt and the other was based on strain gage technology.

**Carbon Fiber Sensors**

Other documents describe the construction of carbon fiber materials. A carbon fiber sensor is simply a piece of felt (nominal thicknesses vary between 1/8" - 3/8" thick) made up of interwinding carbon fibers. The carbon fiber, with the carbon being conductive, can be pictured as a variable resistance. There is an inherent resistance across the felt due to the contact of the carbon fibers in the felt. When pressure is applied, a greater number of fibers make contact and hence the resistance of the felt drops. Hence, when used in a bridge configuration, the change in voltage due to the change in resistance is proportional to the pressure applied. There is a linear relationship between pressure applied and change in resistance up to a saturation point. Physically, at the saturation point, most of the fibers are touching and with an increase in the load, the resistance doesn't cause a proportional change.

There are two primary ways to make a carbon fiber sensor: either over the thickness, transversely, or over the length, longitudinally. Figure 2 Appendix C shows the two construction methods. If used in this application, the
longitudinal sensor would be the preferred method for several reasons. The longitudinal sensor will produce a higher resistance sensor and be more accurate at the same time. It is easy to see that there is more felt between contacts, in essence creating a larger variable resistor. The larger sensor permits sensing of larger pressures at the same time being sensitive to smaller pressures. However, you can not have the best of both worlds in this format as thermal noise proves to be quite significant.

One very attractive feature of the carbon felt is that it is fairly flexible. The felt need not be limited to a flat surface but can be curved around corners and therefore made to more accurately resemble a finger tip. On the down side, when the fiber is bent as described, tension is induced into the felt, lowering the sensitivity of the sensor. Another feature of the felt is that the felt is compliant. Unlike metal and plastic enclosed sensors, the felt offers a surface which has a high friction coefficient and yields with pressure more like human skin. This trait and the pressure sensitivity turned out to be the carbon fiber's best features.

The carbon fiber turned out not to be a dependable sensor for use in this project. The main reasons for seeking other sensors were two fold: one was excessive temperature sensitivity and the other was the fiber instability. The more dominant factor was the fibers temperature sensitivity. As discussed previously, the sensor can be constructed either
using transverse or longitudinal resistance. The carbon fiber has a certain quiescent, unbiased longitudinal resistance. Simple observations show that the inclusion of a carbon fiber sensor in a wheatstone bridge introduces high temperature instability. Graph 1 shows the effect of the carbon fiber sensors in both a quarter bridge and a half bridge.

The carbon felt tested was \( \frac{1}{2}" \times 1" \times \frac{3}{8}" \) thick with a +5 volt, 1 amp power supply across the terminals. The terminals were bonded to the carbon felt using epoxy mixed in with small metal shavings to increase conductivity. The top curve shows the drift versus time due to the temperature stability of the carbon fiber in the quarter bridge. The lower three curves show the average, lowest and highest readings of the sensor in a half bridge. It is obvious that the a half bridge decreases the temperature dependency but not nearly enough to be suitable for this application. Although the graph stops at 450 second (71/2 minutes), the voltage drift continued with time. By letting the sensors rest for 1/2 hour, it was not uncommon for the drift to rise 20-30mv. Also, slight breezes over the fiber drastically dropped the voltage.
The other shortcoming of the fiber was the structural instability and more specifically, the compression under load and the felt/electrical connection. Since the sensor works under the compression of a felt material, it takes some time to return to its original form. This delay time, though not documented, varied with the applied load and varied between 1-10 seconds. This fact alone would limit the grasping cycle to the same relaxing period of 10 seconds. The other problem was the connection between the felt and the electrical circuit.

The felt could have been clamped to an electrode but it would have left a rigid surface on the top. That obviously would have been unacceptable since one of the strengths of the carbon fiber was its pliability. In lieu of that method, the felt was epoxied to the electrodes. The epoxy, as mentioned before, consists of standard epoxy with fine metal shavings added into it to increase the conductivity between felt and electrode. This method allowed a flexible sensor top and still a good electrical connection between the felt and the electrode. Unfortunately, this type of connection could only survive 100 cycles or so before the felt started to rip away from the electrode, basically destroying the sensor. When this happened, several characteristics changed which include an increase in the base resistivity, greater voltage drift and a partial or total electrical contact was lost.
Strain Gages

An alternative and superior sensor can be built using bonded strain gage technology. Unbonded strain gages are not very common and inherently have many problems. A bonded strain gage is a small length of wire encapsulated in a plastic enclosure which is bonded to the test surface (see figure 3). An unbonded strain gage is the configuration in which the ends are bonded to the test surface. There are three reasons why the strain gage based sensor is superior to the carbon sensor described in the previous section. First and most importantly, there is little or no drift from the sensor due to temperature changes in the temperature range of concern (see figure 3, Appendix C for the Resistance/Temp graph.) There will be an initial "warm-up" period which will change the resistance slightly but it stabilizes quickly. The warm-up period is partially needed for the sensor itself but for the electronics as well. The warm up period lasted approximately two minutes before the voltage stabilized. Secondly, with a properly designed spring element, the strain gage sensor will always return to approximately the same starting point once the load is removed. Finally, a strain gage sensor are much smaller and easier to handle than a carbon fiber sensor.

Mechanically, the most critical component of a strain gage sensor is the spring element. A spring element is an element which converts or focuses the applied load to a
dependable predefined strain field. In our case, the spring element is a small piece of sheet aluminum. The most important factor in designing a spring element is to design it so that the spring element is elastic throughout the desired response range. All solid materials have a stress/strain curve which is similar to the one diagrammed at above. There are several key points on the graph but the one that is of interest to us is the yield point. Stress in materials can be classified as being either elastic or inelastic and the dividing line is the yield point. Any stress after the yield point will cause permanent deformation. Most metals have strains at the elastic limit that are approximately 0.2%.
The spring element must be designed so that under maximum expected loads, the material will still be operating in the elastic region.

Since the material chosen is approximately 1\textquoteleft\textquoteleft w x 1\textquoteleft\textquoteleft l x 1/32\textquoteleft\textquoteleft h, simple beam analysis cannot be used. With our predetermined 10 lb maximum force, it was determined that the material would still be in the elastic range and therefore be suitable as a spring element. A finite element program, ANSYS, was used to determine the strain, bending and other mechanical properties of the spring element.

The whole spring element was designed using aluminum due
to its low cost, easy availability, working ease and its mechanical properties. The maximum deflection was also determined therefore determining how far to mount the spring element above the finger. The maximum deflection was 0.005625" which is approximately 1/177". The spring element was mounted on 1/16" aluminum blocks. This allowed for not only the deflection in the spring element but also for the mounting of the strain gage and the routing of the wires as well as any heat dissipation that is generated in the gage. The combination of the strain gage and wire is approximately 1/32" so the 1/16" blocks are sufficient for all considerations.

On the underside of the spring element, the strain gage was installed. The strain gage, see figure 3, is a length of

![Diagram of Strain Error](image)

**Figure 4: Strain Error**
wire which, when strain is induced in the spring element, lengthens and hence the electrical properties, namely resistance, change. The change in resistance when used in conjunction with a Wheatstone bridge, will show a voltage change out of the bridge.

There are several key factors to consider when deciding what type of strain gage to use. The first and most important factor is the gage length. The reason that the gage length is important is that too large a gage will increase the error and too small a gage might miss the strain altogether. Since the strain gage has a physical length, the gage cannot determine a specific strain but instead, the gage measures an average strain over the length of the gage or more precisely, over the gage length. Figure 4 shows an example of a strain in a spring element and the errors incurred for two different strain gage lengths (sensor A and B). It will be shown that sensor A, the larger gage in figure 4, will give a more realistic reading of strain than the pair of smaller sensors, sensor B. Intuitively, one would think that if more accurate readings are required, then smaller strain gages would be necessary. Sensor A is placed in the middle of the sample where the peak strain is located. As diagrammed, the average strain more accurately resembles the peak strain and the error is smaller. If two smaller sensors are used and placed as shown, the strain would be badly misrepresented. Here, the gages miss the strain all together and are measuring only the
residual strains. The smaller strain gages incur a very large error. In my case, the ends of the spring element are anchored and the sensors probably would not measure any strain because those spots are the intersection where the material goes from a state of tension to a state of compression.

The second key factor is the gage geometry. When a strain is induced in the spring element there is not only strain along the length but also along the width. Therefore, to most accurately measure the strain, it would be necessary to have two strain gages, one going length wise and the other going width wise. This could be accomplished using individual sensors or employing a rosette sensor which has 3 sensors 120 degrees from each other. The strain along the width was small enough to ignore. Only one strain gage was used per sensor.

The final factor in the gage selection is the gage resistance. Gages are generally available in 120 or 350 ohms. The selection of either will determine how much heat is dissipated. Obviously, the larger the resistance, the smaller the heat generated since power is equal to the square of the voltage divided by the resistance. One could make the argument that larger resistances increase the noise but rms noise voltage is only proportional to the square root of the resistance. 120 and 350 ohm sensors are the most common types but other resistance types are available.

All of the strain gages have a Gage Factor (GF). The

\[ \text{Power}_R = \frac{V^2}{R} \]
\[ \text{Noise}_R = \sqrt{\frac{4KTR}{R}} \]
gage factor tells the user how the resistance will change over a given strain. Most strain gages have similar GF with the GF varying with different types of spring elements. Typical values are around 2.00 and the gage factor of the gages that I used is 2.05. Quick calculations based on the above show that for the given circumstances, the resistance will change 0.2952 ohms. Using a quarter bridge, there will be a maximum dV of 3.071 mV with a maximum strain of the gage of 1200μ strains (strain=dL/L). An important characteristic of the gage highlighted is that the gage is linear throughout its dynamic range. Hence, if there are only 600μ strains, then the resistance change is half or 0.1476 ohms. This reveals that the sensor is linear, an important characteristic because the sensor circuit needs to be linear. If not, the output signal would be nonlinear and hence more difficult to interpret.

In most sensors, there is a relatively small resistance change which requires a reliable means of outputting these small changes. These sensors are usually placed in a Wheatstone bridge. Wheatstone bridges are configured either as quarter, half or full bridges with the first two diagrammed in figure 1 Appendix C. Because there are very small changes of resistance, proper balancing of the bridge is necessary. The dV of 3.071 mV mentioned above is for a quarter bridge. This project makes use of a half bridge and the dV is 6.14 mV.
The reason that the bridge circuit is so commonly used is that it is highly reliable and outputs an absolute voltage change (e.g. 0 to 0.001 Volts) rather than a relative change (e.g. 2.5 to 2.501 Volts).
Electronics Design

There are three distinct parts to the design of a sensor based control system (see diagram in Appendix C). They are the sensor circuit, control circuit and the response circuit. Of these circuits, the sensor circuit will vary the least between sensing applications. The other two parts, the control and response circuit vary differently between applications. The sensor circuit consists of three sub parts, the sensor, amplifier and resistor Wheatstone bridge. Individual components may vary (e.g. the use of different types of sensors) but the same general concept is used for most sensor designs.

From the last section, it was determined that the output voltage range of the resistor bridge is 0 to 6.14 mV. The desired full scale deflection at the output was determined to be 5 V. Hence, the sensor voltage needs to be amplified approximately 800 times or 58 db. Using hand calculations and then verifying using SPICE (see Appendix D for results), it was determined that the feedback resistance on the op amp needed to be a 100k ohms. It was decided not to use the 100k ohms but to use 90k ohm resistor to avoid driving the op amp.
over 5 volts. This makes $V_{out} = 4.60$ Volts maximum for a 10 lb force. A typical op amp configuration is shown above.

With the sensor, amplifier and bridge designed, the output needs to be converted and sent to the microprocessor. Obviously, this is done by using an A/D converter. The next consideration is how much resolution should there be with the A/D converter. The human hand is a marvelously designed hand in the sense that it can exert tremendous force as well as handle very delicate tasks. We can feel very small forces. The forces I am interested in is between 0 and 10 pounds.

As previously mentioned, the ideal resolution is 0.036 oz (10 mN). A resolution of this magnitude would be of little value on a prosthetic device in the field for several reasons. First, it is easy to control the electrical noise in the lab but virtually impossible in the field. Component wear, dust, noise from engines and transformers would make using this low force difficult to detect. Also, one must ask how often people practically need to feel 0.036 ounces. To put this into perspective, one US penny weighs about 1/16 oz or 0.0625 oz (17 mN). Therefore, 0.036 ounces roughly weighs the same as 1/2 a penny. In order to get an accuracy of 0.036 ounces digitally, the A/D converter would need to have 12 digit accuracy ($\frac{1}{2^{12}} \times 10 \text{lbs} \times 16 \text{ oz/lb} = 0.039 \text{ oz}$.)

A 12 bit accuracy would mean that the LSB voltage value would be 1.22 mV. I opted to decrease the sensitivity and use the 8 bit A/D converter resident in the 68HC11 controller
card. That enables the sensor to have a LSB accuracy of 0.625 oz \((1/2^8 \times 10\text{lbs} \times 16\text{ oz/in} = 0.625\text{ oz})\). The LSB voltage of the 8 bit converter is 39 mV.

The other two parts of a sensor based control system are the response circuit and the control circuit. Both of these are discussed in the next section. The entire control system is as good as its weakest link so all three parts must be well designed.
Motor Controller

Introduction

Motor control is crucial component of this or any motor controlled project. A good motor controller will give the action a smooth final behavior whereas a poor motor controller will reveal choppy movement. Motor control can be broken down into three components; the error junction, voltage and current amplification and the feedback device. With good design of these components, there will be good motor control in the region and around 0 volts for both forward and reverse directions. Figure 6 diagrams the basic motor controller and amplifier with some specifics for this project. The brain of the motor controller is a micro controller and more specifically, Motorola's MC68HC11E9FN1 mounted in the

![Basic Amplifier Theory](image)

Figure 6: Basic Motor Controller
MC68HC11EVBU evaluation board. From now on, the MC68HC11E9FN1 and the 68HC11EVBU will be collectively known as the EVBU or controller unless noted otherwise. A micro controller was used instead of a hard wired system for its programmability and low hardware overhead. The attributes of the controller will be discussed later but two attractive features are the internal converter and the large number of I/O ports. These two functions are used extensively in this project.

Goal

There are four modes of operation to consider: full forward, full reverse, rest and grasping. Full forward and full reverse are similar in function but obviously in opposite directions. Full forward is used for coarse adjustment of the fingers from the open position to the beginning of the grasp. Full reverse is used to reset the fingers back to the neutral position. The easiest mode, rest, is when there is no power delivered to the motor.

The most difficult of the modes of operation is grasping. Grasping is when the finger pressure nearly matches the target pressure. At this time, the current requirements rise to account for the torque generated. The motors will be driven both forward and reverse in this mode to account for external loads acting on the fingers. The power delivered is small since the fingers are performing fine adjustments. Obviously, there needs to be a smooth transition between forward and
reverse for smooth operation.

The DC Motor

In order to fully understand a DC motor control system, it is pertinent to get a basic understanding of the DC motor. In a motor, there are two components which affect the magnitude of the force, they are the field and the armature. Field windings or a permanent magnet are mounted on the frame of the motor, the stator, and produce a magnetic field that the rotor travels through. Armature windings are found on the rotor, or the part of the motor that spins, and current is transferred to the armature through contacts called brushes. In this project, I am using permanent magnet motors to keep the field constant. Therefore, torque control is realized through adjusting the magnitude of the armature current. This form of control will allow a smooth transaction from forward to reverse speeds.

There are motors which reverse the armature and the field by using the permanent magnet on the rotor instead of in the stator. These types of motors are called brushless motors since there is no need for brushes to commutate the current. The advantage of these motors is that they can be used in explosive or other environments since there is no commutator sparking. It is also known that due to the lack of brushes, there are less speed restrictions on these motors. There are several distinct disadvantages however. One disadvantage is
that brushless motors need 3 phase power to operate. A LAT, limited angle torque, motor is a single phase brushless motor but as its name suggests, it can only rotate a certain number of degrees. Also, these motors require much more sophisticated control sequences to operate.

The fundamental principle that the DC motor is based upon is that a current carrying conductor moving through a magnetic field will experience a force proportional \( f_m = BiL \) to the current, length of the conductor and strength and relative direction of the magnetic field. The force developed is directly proportional to the current in the armature and the magnetic field strength. In this case, the field is held constant so the force developed is dependent only on the armature current.

When the motor turns, a voltage is induced in the armature due to the rotor cutting through flux lines of the field and is opposite that of the armature voltage. 

\[
\begin{align*}
e_m &= K_c \phi_f \omega_m = K_{tf} \omega_m \\
\frac{f}{BL} &= e_m \frac{V}{Rm}
\end{align*}
\]  

Lenz's law says that this voltage has to have a polarity opposite that of the armature current. This induced voltage is called the back emf, \( e_m \). The above equation shows that \( e_m \) is proportional to the motor speed and the field flux. However, since the field flux is held constant, via the permanent magnet motors, the back emf is therefore proportional only to the motor speed.

This project uses current control techniques to control
the generated torque. Therefore, current in the armature needs to produce enough torque to overcome the load requirements and also to overcome the effect of the back emf.

Torque, current, back emf and speed are all closely interconnected. Using equations 3 and 4, several different scenarios can be investigated and figure 7 aids the discussion. Assuming a light load on the motor, then the motor compensates by generating extra force. According to equation 3, the current to the motor must increase. The speed of the motor must the decrease and in accordance with equation 4a, the back emf must decrease. The relationship between force and speed are shown in figure 7.

If the load increases, the above effects increase. The current rises more and the back emf and speed decrease. Finally, the load becomes so large that the motor stops. This point is known as the
stall torque. Since the motor is stopped, the back emf=0 and all the electrical power is dissipate as heat in the motor. On the other end of the scale is if the motor had no load on it or the no load state. According to equation 46, \( f = k(v - e_m) \), \( V \) should = \( e_m \) and concurrently, the current to the motor = 0. In practice, there is some current in the no load state but it is small.
Control

In any engineering problem, the question of how much modeling is always a factor. Too much modeling usually makes the model too complicated and impossible to analyze. On the other hand, too simple of a model will make the results questionable and more often than not, ineffective. Throughout the control analysis, approximations are made in order to keep the transfer equations reasonable yet detailed enough to represent the system accurately.

As mentioned previously, the quality of the control system determines the performance of the system. One doesn't want to design a control system that is oscillatory because the system will appear choppy. On the other hand, if the system is over damped the system will take a long time to respond. The system needs to be modelled to determine its characteristics. Since the system is built with several different sections, it is possible to model each section mathematically. Then, the entire system's operating characteristics can be found.

A good start is to determine what transfer function we are going to work with. The output of the system will be torque and the input will be voltage into the PWM. Since torque is directly proportional to current, the transfer function is current to voltage. Therefore, the control system of concern is from the output of the D/A converter to the torque on the fingers which is represented by the current.
Overall System Control Block Diagram

PWM Control Block Diagram
Mathematically models are most easily manipulated using the Laplace transform. Figure 9 shows the Laplace transform of both the overall and PWM control scheme. The overall control scheme includes 2 feedback loops: a torque loop with in the PWM and a force loop. First, the PWM control circuit will be analyzed. After taking the information and developing a transfer function, the Laplace transform can then be interpreted graphically through Bode and Nyquist plots. These methods illustrate phase shifts, damping, amplification and other critical data faster and easier than performing the tasks mathematically.

The system can be broken into 4 distinct parts; the level shifter, error amplifier, PWM and motor and the current amplifier. The input to the PWM system is a bipolar voltage ranging from 5 volts to -5 volts with 5 volts from the output of an external D/A converter (see schematic drawings Appendix C). The system first converts the bipolar input to an unipolar equivalent. The positive input to the level shifter is +5 volts and the other is the input voltage. The transfer function of this section is simply \( \frac{R_2}{R_1} \).

The other parts in the feed forward loop are an error amplifier, motor model and output transistors. The feedback loop contains a current amplifier from the output transistors and a pass filter. Analysis of these parts were similar and models were generated. The results are shown in figure 9 and explained in Appendix D. Torque control is accomplished from
a current feedback circuit attached to the output drivers. Since op amps have high input impedances, relatively no current is taken by the input of the driver FETs. The current sensing transfer function is the ratio between the transconductance of the op amp and the sensing resistors ($R_{S1}$ or $R_{S2}$).

$$G_{MO} = \frac{I_M}{V_{TH}} |_{s=0} \quad (5)$$

$G_{MO}$ is the DC transfer function from the input of the comparator to the output, motor current, of the amplifier. As shown in Appendix D, $G_{MO}$ is a function of the motor resistance, supply voltage and the internally generated reference voltage and therefore relatively easy to determine. Looking at the Laplace block diagram, to stabilize the current loop, the poles must cancel. From that, it can be deduced that $RC=Lm/Rm$. With this stipulation, the transfer function can be calculated as shown in the equation above. The transfer function reduces to $0.048/Rs$ for $\omega=0$. Since $Rs \leq 0.88\Omega$ for $Io=0.5A$, the minimum DC transfer function is $0.054\, A/V$. The block diagram reduction and results are shown in greater detail in Appendix D.

CC, a control software package, was run with the PWM transfer function and the results are shown in Appendix C. The

$$\omega_d = \sqrt{1-\zeta^2 \omega_n} \quad (7)$$

$$s^2+2\zeta \omega_n s+\omega_n^2$$
root locus graph shows us the stability of the PWM control system. This graph shows that the system is stable for any gain value. Root locus, upon further inspection, reveals the natural frequency and the damping factors. Using the root locus, fig. 1 Appendix C, the undamped natural frequency, \( \omega_n \), is the length of the vector from the origin to the closed loop pole. System damping, \( \zeta \), is derived from the angle of the same vector to the X or real axis. With the combination of these two system variables, the damped natural frequency, \( \omega_d \), is found as shown in the equations above.

Another way of illustrating the response is with the Bode diagram, Appendix C. The Bode diagram illustrates the response at different frequencies, its stability and other system characteristics. Stability is achieved when there is a positive phase margin or gain margin. Figure 2 shows that the system is stable up to the second breakpoint. The phase margin is about 48° and the gain margin is low, about 6 db. The time domain plot which shows the real world response is illustrated in Appendix C.

With the transfer function of the PWM established (equation 6) the entire transfer function can be determined. The input to the whole system will be a reference voltage, \( V_{\text{ref}} \), and the output will be the force at the sensors. The block diagram is illustrated in Figure 7. In the following analysis, friction, unless noted otherwise, will be ignored. This was done to simplify the overall transfer function and
keep it to a second order system. The old control saying is "The more you estimate, the more the error" so these estimates were done when the friction was 10% or less than the model.

The output of the PWM is current. According to basic DC motor design, current and torque are directly related by the motor constant. Motor inertia has already been accounted for in the PWM TF so, current to torque is $K_T$. The torque is representative only for the DC motor and not the output of the gearbox. The gear ratio from $T_{in}$ to $T_{out}$ is 270:1. Unless unusual conditions exist, a good approximation of gear train efficiency is a maximum loss of 5% per gear pass. Here, there are components of friction between the gears can be ignored. The friction is proportional to the motor speed but is negligible compared to the force in the gears.

The output of the gearmotor then transfers the load to the finger. This consists of the drive sheave, jacket and cable assembly and the load sheave. The jacket and cable assembly usually is transparent but due to the bending involved, some of the load is lost here. I am assuming the output of the gearmotor is $x$ in lbs. The drive sheave has a diameter of $\frac{1}{2}$" so the output $y$ force is $x$ in lbs/ $\frac{1}{4}$"=$4x$ lbs=$y$. The jacket loss depends on how much bending occurs. Jacket bending wants to be limited to 270° and here will be approximated to be 0.9. So the cable force at the base sheave is $0.9\times4x$ lbs. The base sheave has a $\frac{3}{4}$" diameter so the torque around the pivot point is $(\frac{3}{8})*(0.9)*4x$ in lbs=$\frac{3}{2}*0.9$
in lbs. Finally, the load will be approximately 1.5" from the base sheave so the force transmitted to the sensor is $\frac{1}{2} \cdot 0.9 \cdot \frac{1}{3} \cdot x = 0.9x$ lbs.

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**Overall System Control Block Diagram**

The feedback loop includes the strain gage, sensor, bridge and amplifier output. The input to the feedback is force and the output is voltage which is fed back to the microcontroller. The first model is that which converts force into strain. A maximum force of 10 lbs induced a strain of close to 1200μ strains in the metal. There of course is error due to the physical nature of the strain gage but that would be difficult to model since the error is slightly non-linear. Otherwise, it is assumed that the strain is transferred directly to the strain gage.

The strain then changes the resistance in accordance with the gage factor and the strain. This model is detailed further in Appendix D and the output is dV from the Wheatstone Bridge. Finally, dV is amplified to have a 5V maximum output. The op amp is slightly approximated by saying that the system
will be operated at least one decade below the break frequency. If the system was operated above that frequency, the output would drop approximately 20 db/dec according to standard op amp design.

Solving this transfer function manually would be an accounting nightmare. As indicated, the approximations made kept the transfer function to a second order system with two poles and one zero. Appendix C includes time response, root locus and bode plots illustrating the response of the overall system. The root/locus plots show the damping and natural frequency for a certain closed loop gain. The Bode plot indicates stability as indicated by the gain and phase margins. Finally, a time response to a unit step input is also diagrammed.
Microcontroller Features

There are several microcontrollers available on the market today. Most are highly advanced designs with a price to match. These microcontrollers make use of high level languages, emulators and PC based control systems and are designed more for large scale controls. Motorola has several microcontroller systems and the one selected for this project was the EVBU kit.

The Motorola EVBU kit can be configured to run with the before mentioned 68HC11E9 chip or the 68HC711E9 chip. There are several transparent differences between the two but the main difference between the two controllers is the way the EPROM is used. The HC11 chip has its 12K EPROM dedicated to the BUFFALO monitor program while the HC711 chip leaves the 12K EPROM free for the user to develop. Besides that, the two chips are the same and the ensuing discussion applies to both.

Two of the more attractive features of this microcontroller are the resident A/D converter and the 38 general purpose I/O pins. The following is a partial list of features for the controller:

- 12 Kbytes of on-chip EPROM.
- 512 bytes of on-chip EEPROM.
- 512 bytes of on-chip RAM.
- 16 bit timer system.
- 8 channel, 8 bit analog to digital converter.
- 38 general purpose input/output pins; 16
bidirectional,

-11 input only, 11 output only;

The EVBU A/D converter does not require an external sample and hold circuit. The A/D input circuitry has a built in capacitance to hold steady the input voltage to reduce the error. This project makes extensive use of the A/D as the main input as well as the 38 I/O pins.

A final consideration was the controllers physical size. Space is a premium in a prosthetic device so the controller had to be small. The EVBU has a small footprint of about 3"x5" which includes a small wire wrap area. That size could be reduced to about 3"x3" if the RS-232 connector, timer chips and other miscellaneous devices were eliminated.

Programming

The EVBU unit is a programmable control chip which has many desirable features. These were explained in the previous section. The controller has two powerful editing tools which allow the EVBU to be written and read fairly readily. The EVBU has several areas in its RAM which are user accessible. The 12K ROM is dedicated to one of the controllers editing tools, the BUFFALO program. BUFFALO is an acronym representing Bit User Fast Friendly Aid to Logical Operations. The other editor is called PC Bug which is run directly from the PC. PC Bug is a PC based version of the BUFFALO program. And instead of downloading the program to the EVBU, it remains
resident in the PC. It is designed mostly for the newer chip sets like the 68HC711E9 chip which are one time programmable only. I used the BUFFALO program exclusively. Communication to the EVBU board is through a RS-232 cable using a terminal emulation program like Kermit, Procomm or MS Windows Terminal. All three were used at different times but MS Windows Terminal program was the best to use since it allowed easier access to a text editor and simultaneous display of both.

There are two ways of programming the EVBU: directly or indirectly. To program the EVBU directly requires the user to know the proper op codes and operands. This method is highly suspect and is prone to many errors. The other way to program is the indirect method which starts by writing assembly language in a text editor. Motorola's assembly language has a complete set of standard codes as well as some other specialty codes. The user is free to edit the program as he pleases. Motorola has included some assembler directives which allow variables to be equated to some values. This allows the user to write a program more freely.

When the user is ready to download his program, he needs to translate it into machine code called an S record. A cross compiler translates the assembler directives and code into the S record, machine code, which includes the op codes and addresses. During down loading, erasure and programming both require 10 milliseconds per byte. My S record was about 600 bytes so downloading takes about 6.0 seconds.
Several functions are required from the controller. These include reading the sensors via the A/D converter, start/stop motion of the fingers and forward and reverse actuation of the motor. Inputs are processed through port E exclusively except for the pressure control which is input through port A. All the motors are outputted through port B. Port C provides the demultiplexing and dictates which motor is controlled next. The program listing is found in Appendix A along with the S record.
Finally, with the controls completed, motors selected and sensors developed, the last item to discuss is the electrical/mechanical interface or the servo amplifier. The servo amplifier has to be able to deliver enough power to the motor without destroying itself. There are several types of specific amplifiers but servo-amplifiers can be classified into two basic categories according to what they use to drive the servo motor. One, which is referred to as the linear servo amplifier, uses bipolar transistors in their linear or active regions; the other is the PWM servo amplifier which drives bipolar transistors or MOSFETs in the ON-OFF mode, using the pulse width modulation technique.

The first type of servo amplifier, linear, is the less efficient of the two. The linear amplifier has the BJTs on all the time. Therefore, the power is either delivered as energy to the motor or dissipated as heat in the transistors. Linear amplifier configurations can be easily made to drive the motor in either forward or reverse using a push/pull configuration. The push pull method also needs a bipolar voltage source which means offsetting the voltage 180°. This is necessary so that the motor can be driven both ways. A reduction in power dissipation can be accomplished by cycling the supply voltages between ON and OFF. Energy loss in the transistors will be reduced since the resistance will be high (OFF) or its lowest (ON).
PWM, is such a method that employs MOSFETs and operates with them either fully on or fully off. PWM is also flexible enough to be able to drive both DC and AC motors.

The amplifier stage consists of 4 MOSFETs arranged as shown in Figure 10. This configuration is commonly referred to as an "H Bridge". Pulsing of Vout is accomplished by the combination of activating switches 1, 2, 3 and 4 at varying time. The width of the pulse is determined by how long a combination is energized. Referencing figure 10, when switches 1 & 4 are ON and switches 2 & 3 are OFF, Vout matches Vcc and there is a positive pulse or the ON state. Then when switches 2 & 3 are on and switches 1 & 4 are off, Vout equals -Vcc or the OFF state. It is easy to see that the small power losses in the FETs are due to the fact that only one of the FETs on one side is on at a time. Additionally, while linear amplifiers use a push/pull method, PWM can generate bipolar voltages from a unipolar source to drive the motor forward or reverse.

The output of the PWM is then used to drive the motor. The power delivered to the motor depends on the switching duty of

\[ T_{\text{Motor}} = i_a \cdot k_T \cdot \Phi_p \]  

(8)
the PWM. Switching duty is the ratio of the time spent in the ON state to the time spent in the OFF state (see figure 4 Appendix C). As the load increases, the motor torque will increase in turn lowering the speed. Figures 7 and 8 show a graphical relationship between these three variables. The increase in the current is fed back and will increase the ON state which will increase the current at the output of the PWM.
Experimental Results

There are two areas in the circuitry which require precision components: The Wheatstone bridge and the PWM motor driver. Ordinary 5% resistors can be used on one side of the bridge but they must be used in conjunction with trim pot resistors for fine tuning. The reason is simple since the next stage after the Wheatstone bridge, that signal is amplified 800 times. A small difference in the bridge will drive the output out of the design range. For instance, I designed the input to vary between 0-5 volts. If there was a \( \text{dv bridge error of 6.25 mvolts} \), the output of the amplifier would be 5 volts basically telling the computer there is 10 lbs of load on the sensors. To make use of the full voltage swing from 0-5 volts, the output of the bridge has to be 0 volts under no load conditions.

Despite having precision electronics and balanced bridges, heat generation proved to be a minor nuisance. This only occurred at the input stage due to the voltage levels being worked with. A warm up period of 2-3 minutes is necessary to stabilize the op amps and resistors. If under static air conditions, then no error will occur due to temperature drops. However, the circuits were not enclosed and were subject to air currents cooling off the components. Air currents were seen to drop the voltage 0.1 volts.

The other area that precision components are necessary is
with the PWM motor driver. The current sense resistors are recommended to be either non-inductive resistors or a maximum of 2% precise resistors. The 2% resistors were metal film filled to reduce the inductance usually related with carbon resistors. The precision is required due to the help keep the inductance of the circuit to a minimum.

The PWM motor driver chip came as a 15 pin V package. The pin configuration was not conformable the proto board in any orientation. An adapter was made using a 15 pin computer cable adapter and attaching leads to conform to the proto board layout. The PWM chip also came with a small heat sink on it. The chip became fairly warm during motor operation. A small heat sink should have been attached to it to help keep the chip cool.

The EVBU unit is a powerful and easy system to use but it also has some fickle requirements. One such requirement is that the communication to the EVBU had to be done through either COM port 1 or 2. Using any other COM port did not establish a reliable connection. Once a reliable connection was established, it was easy to download programs and to check registers.
Conclusion

A prosthetic hand has many facets that need to be taken into consideration. Most of what other people see is the mechanical part of the hand but it is the electronics that make it work. Indeed, there are some aspects of the mechanical design that I had to compromise. For instance, friction analysis was often estimated but in a real world system, it would need to be accounted for.

Mechanically, the hand should be made of metal. Metal offers better stability, higher loads and durability. The chosen wooden hand was adequate but many compromises were made, for instance the cable routing. The jackets holding the cable are a problem. They don't work effectively. Under loads, instead of transmitting the force to the fingers as designed, the jacket compressed. Only after the jacket have fully compressed is any work transmitted to the load. Additionally, this puts unfavorable stresses on the cable.

It was found that carbon fiber sensors are unacceptable for this application. Carbon fiber sensors have their use in other applications especially when high temperatures (100°C and above) are encountered. Reasons for incompatibility are given above and need not be repeated here. The strain gage devices worked well with the addition of a rubber skin. The rubber added a good gripping surface as well as a little more compliancy to the fingers. A thin layer of rubber was used so
as not to decrease pressure sensitivity substantially.

Electronically, the load side of the PWM was the most critical area in terms of component accuracy. Precision resistors and peripheral device location were both key elements for the PWM to function properly. The other sensitive part of the circuit was the Wheatstone bridges. Extreme precise balancing of the bridges wasn't necessary since the EVBU compensated slightly upon initialization.

The EVBU evaluation kit provided easy modification of programs and control. The simple assembly language allowed programs to be written on a PC with a line editor and cross compiled to Motorola's machine language. In addition, the 2 MHz clock speed allowed for a sampling rate of around 100Hz.

Although, not a very solid model of a prosthetic, this project lays the foundation for future work. There are several areas that could be expanded upon. First, the sensors. Although they are accurate, stable and have a quick response time, they require a rigid body to function. But generally, a sensor needs to be developed which is as accurate as the strain gage but has better compliance. Human finger tips have soft pliable tips. I envision a fluid filled sac acting as a spring element instead of the metal plate. A sensor like this could both act as a tactile sensor and also provide some give at the place of contact. Work could also be done with sensor arrays to make them usable for prosthetics. Preprocessing of the signals before they are sent to the hand
controller could make the system small enough for a prosthetic.

Another area of future work is to remove the controller and to implement feedback to the body via sensor substitution or neurally. Both methods reduce or eliminate the need for a controller. The removal of the controller could allow the whole electronics package to be reduced and installed in a "forearm".

Still another area of future work would be to implement a wrist with 2 DOF, rotational and forward and back. The hand previously described is fixed upon the forearm. With a wrist, it could rotate and pick up objects without requiring too much effort on the part of the amputee. This would lead to a more natural prosthetic. The world of prosthetics still offers many fields for study. Someday, a "bionic" part will be feasible.
Bibliography


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Appendix A - Microcontroller Listing

Thesis.lst

* Controller for a three finger prosthetic hand
* By Paul Noniewicz-Spring 1992
* For Thesis in Master of Science in Electrical Eng.
* Version August 30

* Assembler Directives
* Equates - Registers which will be addressed using IND,X

REGBAS EQU $1000                STARTING ADDRESS FOR BLOCKS
PORTA EQU $00                   PORTA FOR THE RESET INPUTS AND
START/START PORTC EQU $03      PORTC FOR THE START/STOP AND
RESET PORTB EQU $04             PORTB THE OUTPUT TO THE MOTORS
DDRC EQU $07                   DATA DIRECTION FOR PORT C
PACTL EQU $26                  PULSE ACCUMULATOR CONTROL
ADCTL EQU $30                  A/D CONTROL REGISTER
ADR1 EQU $31                   A/D RESULT REGISTER #1
ADR2 EQU $32                   A/D RESULT REGISTER #2
ADR3 EQU $33                   A/D RESULT REGISTER #3
ADR4 EQU $34                   A/D RESULT REGISTER #4
OPTION EQU $39                 OPTION REGISTER
REF1 EQU $00                   REFERENCE VOLTAGE FOR SENSOR SET 1
REF2 EQU $01                   REFERENCE VOLTAGE FOR SENSOR SET 2
REF3 EQU $02                   REFERENCE VOLTAGE FOR SENSOR SET 3
PRESSURE EQU $04               STORE PRESSURE VALUE HERE
CONTACT EQU $07                CONTACT PRESSURE FOR GROSS-.141
LBS HOLD EQU $08                Hold tank for pressure

* Initializiation
*
ORG $B600                    UTILIZING THE 215 BYTES IN EPROM
LDS #$0047                   TOP OF USER'S STACK AREA ON EVBU
LDX #REGBAS
LDAA #$10111111              ENABLED A/D AND SET CSEL TO E CLOCK
ANDA OPTION,X
LDAA #$00                   FORCES A7 AND A3 TO INPUT MODE
STAA PACTL,X
LDAA #$FF                    SETTING PORT C TO OUTPUT MODE
STAA DDRC,X
LDAA #$00
STAA PORTC,X                Deactivating the PWM and all S/H

* Port E: A3=External start. A0-A2=sensor inputs.
* A4=External start. A5-A7=finger resets inputs.
* Attaining reference voltages and amount of pressure to apply
* Port C: activating the S/H and turning ON/OFF the PWM
Appendix A-Page 2
Thesis.lst

* line 46 xxxxx0000 1-3:S/H:1=on 0=off 0:0=PWM off, 1=PWM on
* Port A: Set up to determine the amount of pressure
* xxxxx000.
*
** Main program
******************************************************************************
* Using Port E to read the ON/OFF switch
* Wait first until the start switch is hit

STARTA  LDAA  #00010000  ACTIVATING PORTE-SET #1

START  LDAA  ADCTL,X

ANDA  #80
BEQ  START  WAITING FOR THE A/D TO BE DONE
LDAA  ADR4,X  DONE
ANDA  #F0  Waiting for start switch
BEQ  STARTA  GOTO STARTA, BIT 3, IS LOW

LDAA  #8
STAA  PORTC,X  Activate the PWMs
LDAA  ADR1,X  Sensory reference voltages.

STAA  REF1
LDAA  ADR2,X
STAA  REF2
LDAA  ADR3,X
STAA  REF3  Done Storing Reference Voltages
LDAA  PORTA,X  Get amt of pressure to exert
ANDA  #07  GET RID OF TRASH WHICH WILL BE THERE
ROLA
ROLA
ROLA
ANDA  #38  GET RID OF TRASH IF ANY IN THE CARRY
STAA  PRESSURE  LOAD PRESSURE INTO $04

* Starting to close the hands, first with the gross closing
JSR  GROSS  GROSS CLOSING OF THE HAND
* BACK, time to open the fingers
* CLOSING THE FINGERS
JSR  CLOSE
BRA  STARTA  REDO THE WHOLE KIT AND

KABOODAL
*
* End of main program
******************************************************************************
*
* SUBROUTINE - Returning the fingers to the natural or open position.
*
CLOSE  LDAA  #00010100  Prepare to read the reset

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Thesis.1st

Location of switch in second set

Goto CONCLUDE if switch is thrown

$80=MOTOR AT REST

FF+=5V=SWITCH CLOSED

Is finger 1 closed ?

Will branch if 1=0

set motor in full reverse

Activating the right S/H

Outputting full steam astern

Deactivating the right S/H

Done, go to the next finger

Saving B to compare later

SETS FINGER 2 IN FULL REVERSE

SETS FINGER 3 IN FULL REVERSE

Deactivating the right S/H

Done, go to the next finger

Comparing all motors together

if 1=0, start again

Deactivate all the PWMs.

Return from the subroutine

* * * * * * End of SUBROUTINE CLOSE

*****************************************************************

* SUBROUTINE - Gross closing of the fingers until contact is made

* Gross will take us so that dV is <=0F so that fine is more precise.
APPENDIX

Thesis.1st

1=Multiple conversions for 4 channels

Load ADR4,X

ANDA #$00

BNE GETOUT

LDAB #$09

Start of finger 1

PSHB

LDAA ADR1,X

LDAB REF1,X

JSR CONVERT

STAA HOLD

End of finger 1

LDAB #$0A

Start of finger 2

PSHB

LDAA ADR2,X

LDAB REF2,X

JSR CONVERT

ANDB HOLD

STAB HOLD

End of finger 2

LDAB #$0D

Start of finger 3

PSHB

LDAA ADR3,X

LDAB REF3,X

JSR CONVERT

ANDB HOLD

BRA GROSS

GETOUT

RTS

Return from subroutine

******* END OF SUBROUTINE GROSS ***************

* SUBROUTINE—Converts relative pressure to appropriate digit.

PRESS

CONVERT

SBA A-B into A

BLE SUBZERO No pressure, go whole hog

SUBA Pressure some pres., measure against

GOAL

BLT LESSTHAN

ANDA #$7F Too much pressure, back off

BRA DRIVE

LESSTHAN EORA #$FF Not enough pressure, get it going

ORA #$80

BRA DRIVE

SUBZERO

LDAA #$FF Get the right S/H

DRIVE

PULB

STAB PORC,X Activate the right S/H

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STAA PORTB,X        Output the power to the S/H
LDAB #$00
STAB PORTC,X        Deactivate the right S/H
RTS                  ** Returning from the subroutine *

******** END OF SUBROUTINE CONVERT **********
Approximate size of an egg <1.5" in diameter>
Egg in question is a large white Grade A.

Approximate finger flexor angles are: proximal=17
distal=22
Two 'Index' fingers are angled at approximately 7 degrees.

Top with fingers to verify clearance
1/8" dia x 1/4" length peg.

Sheave Details

Fingers Base
Top view of Motor base
Appendix C - Drawings
Wheatstone Bridge and Carbon Fiber Construction

1/4 bridge: Acceptable if only one sensor is available. Drift contributes greatly to the error.

1/2 bridge: Much better. Drift in one sensor is nearly balanced by drift in the other sensor greatly reducing the error.

Figure 1: Resistor Bridge Configuration

Figure 2: Carbon fiber sensor construction
Appendix C-Page 2
Apparent Strain and PWM Wave forms

Figure 3: An atypical Temperature Induced Apparent Strain

Figure 4: Pulse Width Modulator Input and Output
3 Finger Prosthetic hand
Block Diagram

Typical Sensor Setup

=Digital Lines
=Analog lines

Start/Stop:Reset Button
EVBU- MICROCONTROL
EVALUATION UNIT
Appendix C—Page 4

Control System Block Diagram

Control System: Block Diagram

Start

Initialization of sensor voltages

No

Start Switch Hit?

Yes

Sense Pressure

Calculate Relative Pressure

Near Target Pressure

No

Keep motor on

Yes

Turn Motor off

Have all three fingers reached the target?

Yes

Sense and Convert Pressure

Output to PWM

Next finger

No

Finger Reset?

Yes

Reset Request

No

Reverse Motor

Turn Motor Off

No

Are all three fingers reset?

No

Finish

Yes
Appendix C-Page 7
Bode and Root locus Diagrams

Above: Bode Plot showing a gain margin of 5.774 db indicating stability. Below: Root locus diagram of the open loop response. Also plotted is the closed loop critical damping gain.
Appendix C-Page 8
Bode and Root locus Diagrams

Time response to a unit step input

Peak is 0.979

Above: Time response of the overall system due to a unit step input. Below: Bode Plot of the PWM control system illustrating the significance of the PWM.
Appendix D - Calculations
Muscle Wire and Torque

1. Muscle Wire Calculations

\[
\begin{align*}
150 & \text{um} & 1 \text{ mm} & 1 \text{ cm} & 1 \text{ in.} \\
1000 & \text{um} & 10 \text{ mm} & 2.54 & \text{cm} \\
\end{align*}
\]
\[= 0.0059 \text{ in} \]

Area = \(\pi r^2 = \pi \left(\frac{d}{4}\right)^2 = 3.141 \times (0.0059/4)^2 = 27.4 \text{ u in}^2\)

The muscle wire has a strength of 2.5 tons/in\(^2\) so,
\[27.4 \times 10^{-6} \times 2.5 \text{ tons/in}^2 = 68.5 \times 10^{-6} \text{ tons.}\]

\[68.5 \times 10^{-6} \text{ tons} \times \frac{2000 \text{ lbs}}{1 \text{ ton}} \times \frac{16 \text{ oz.}}{1 \text{ lb.}} = 2.191 \text{ oz} = 0.137 \text{ lbs}\]

The maximum force needed is 10 pounds
\[10 \text{ lbs} / 0.137 \text{ lbs} = 73 \text{ wires}\]

2. Finger Torque

\[F_1 = (10-X) \text{ lbs}\]
\[F_2 = X \text{ lbs}\]

\[T_1 = D_1 \times F_1\]
\[T_2 = T_1 + F_2 \times D_2\]
If the total force on the finger is 10 pounds, then
\[T_2 = (10-X) \times D_1 + X \times D_2\]
\[T_2 = 10-X + 1.5X\]
\[T_2 = 10 + 0.5X\]

If all 10 lbs are on the proximal finger then
T2=15 in lb. Else, T2=10 in lb.

The lower pulley is 3/4". If the entire load is concentrated in F2, then T2=10 in lb and F4=3/8"*T2 or F4=26.67 lbs
the required motor torque to drive this load is \(1/2 \times 26.67 = 13.3\) in lbs.
Appendix D-Page 2
PWM Control

\[ \frac{R_2}{R_1} \quad \frac{R_4}{R_3} \quad \frac{1 + SRC}{SR + C} \quad \frac{G_{me}}{1 + \frac{C}{R_m}} \quad \frac{R_p}{1 + SR + C} \quad \frac{R_s}{R_s} \]

- \( R_1 = 12\text{K ohms} \)
- \( R_2 = 7.2\text{K ohms} \)
- \( R_3 = 5\text{K ohms} \)
- \( R_4 = 400\text{ ohms} \)
- \( R_f = 560\text{ ohms} \)
- \( R_s = R_{s1} = R_{s2} \)
- \( R = 22\text{K ohms} \)
- \( C_f = 47\text{n farads} \)
- \( C = 47\text{n farads} \)
- \( V_r = 8\text{ volts} \)
- \( V_s = 20\text{ volts} \)

\( R_{\text{max}} \cdot I_{\text{motor}} \leq 0.44 \)
\( I_{\text{motor}} = 0.5 \text{ Amps} \)
\( R_{\text{max}} \leq 0.44 \)

**PARTIAL PWM SCHEMATIC**
Appendix D-Page 3

PWM Control

To aid stability, pole cancellation in the feed forward loop is used. The block reduction due to the cancellation is shown here at the right.

Block Cancellation:

\[ \frac{1}{1+SRC} = \frac{1}{1+\frac{Lm}{Rm}} \]

or

\[ RC = \frac{Lm}{Rm} \]

The transfer function for the PWM system is:

\[ \frac{I_{\text{motor}}}{V_{\text{inp}}} = \frac{TF = \frac{KG}{1+KGH}}{1+R_sR_f} \]

\[ TF = \frac{R_2R_f}{R_1R_3} \cdot \frac{G_mR_f}{1+G_mR_fR_s} \cdot \frac{1}{1+G_mR_fR_s} \cdot \frac{1}{1+R_2R_fC} \]

\[ TF = \frac{R_2R_f}{R_1R_3} \cdot \frac{G_mR_f}{1+G_mR_fR_s} \cdot \frac{1}{1+G_mR_fR_s} \cdot \frac{1}{1+R_2R_fC} \]

or finally,

\[ TF = \frac{R_2R_f}{R_1R_3} \cdot \frac{G_mR_f}{1+G_mR_fR_s} \cdot \frac{1}{1+G_mR_fR_s} \cdot \frac{1}{1+R_2R_fC} \]
Gm = Vs / (2RrVr) = 20 / 16 * (0.88) = 1.42

The natural frequency is found in the equation above to be:

\[ \omega_n^2 = \frac{G_m R_s}{R_t C_f R_4} = \frac{1.42 * 0.88}{47 * 10^{-9} * 400 * 560} = 2.525 \times 10^9 \]

or

\[ \omega_n = 50200 \]

So the damping coefficient can be found by:

\[ 2\omega_n \zeta = \frac{1}{R_t C_f} = 37993 \]

or \( \zeta = 0.378 \).

Inserting the variables into the rest of the transfer function, the transfer function becomes:

\[ TF = \frac{7200 * 400}{12000 * 560} \frac{1 + s(2.63 \times 10^{-5})}{s^2 + s 37993 + 2.525 \times 10^9} \]

At DC conditions, the transfer function reduces to:

\[ TF = \frac{I_{motor}}{V_e} = 1.23 \times 10^9 \frac{1 + 0}{0 + 0 + 2.525 \times 10^9} \]

\[ TF = \frac{I_{motor}}{V_e} = 0.487 \]
Appendix D-Page 5
PWM Control

As indicated in the text, to solve the overall transfer function would be messy. With the simplifications noted, the block diagram reduces to:

Again, using the TF definition, the overall transfer function is:

\[ TF = \frac{34\, PWM}{1 + 17\, PWM} \cdot \frac{10^4}{1 + s10^4} \]

Which yields a third order system or:

\[ TF = \frac{34(s0.0000326 + 0.136)(s10^5 + 1)}{s^3 0.000045 + s^2 1.88 + s250000 + 4.812} \]
Output of input opamp with a voltage of 6 mV ac
Vita

I was born in Bristol, Connecticut on August 27, 1964 to Stanley and Elizabeth Noniewicz. I attended college at the University of Vermont in Burlington Vermont and received a Bachelor of Science Degree in Electrical Engineering in May of 1986. While at UVM, I graduated in the top third of my class and in addition to additional academic achievement, I also received numerous accolades in sports and ultimately appeared in Sports Illustrated.

Upon graduating from UVM, I joined a small consulting firm, Luchini, Milfort and Goodell, in Wethersfield Connecticut and was eventually transferred to Boston to start up a branch office. After working for 4 years, I returned to school and began studying for a Master of Science in Electrical Engineering at Lehigh University in Bethlehem Pennsylvania from whence this document comes from. I graduated from Lehigh in October, 1992. The best and the rest is yet to come.
END OF

TITLE