Design of a Robotic Hand with Flexible Grip for Prosthesis

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As part of the Summer Training (2003) in Central Electronic Engineering Research Institute (CEERI), New Delhi, under the guidance of Mr. Amrik Singh, Robotics Division.

CERTIFICATE

1st August, 2003

This is to certify that Sameer Singh, Final Year B. E. student, Electronics and Communication Engineering, Netaji Subhas Institute of Technology, has worked with me as part of his summer training in June-July 2003. Under my guidance, he has worked on and designed the Robotic Hand.

This design is being implemented by the Institute.

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Abstract

This paper describes the complete design of a Robotic Hand which can be used for prosthesis. This design aims to overcome the gripping problems in earlier prosthesis, while still maintaining the simplicity of design, miniaturization and lightness. The objective has been to design hand which can grasp objects of a variety of softness and shape, and grip tightly without damaging them. To achieve this, a backbone of a spring system has been used in conjunction with the actuation system. Three of the five fingered hand have 2 DOFs while the rest two have only 1 DOF, which is more than those available in currently available prosthetic hands (there are, however, only two active DOFs). Sensors form a closed loop feedback to detect and avoid slippage in case of a change in weight of the object. The input from the user is taken by using electromyogram (EMG) classification, better known as myoelectric signals. This results in a hand which can grasp a multitude of objects and grip with force as much as is required to avoid slippage, at the same time it is comfortable and easy to use for the user.

Contents

List of Figures

This is a list of figures appearing in this report.

About CEERI

Pt. Jawaharlal Nehru laid the foundation stone of CEERI on 21st September, 1953 in Pilani, Rajasthan. The Institute commenced its activities from year 1958. Its initial work related to the development of microwave vacuum tubes and electronic systems in areas such as industrial electronics, communication acoustics. The semiconductor division was added in mid 1960s. The centre now undertakes research and development activities for user organizations and industries. Currently the areas of research and development interests are:

- CAD of digital integrated circuits
- Speech technology
- Robotics
- Museum electronics, AV systems
- and assistance to the national technology mission in other ways

Since research and development work is taken up on sponsorships basis, the results find immediate applications with the users or in the products taken up for manufacture. The know-how of the technical capabilities and years of intensive research and development experience make CEERI the ideal partners to Industry.

The Products Manufactured By CEERI

- **Power Darlington Transistor (100A & 300A)**: It is a monolithic epitaxial double diffused transistor of the planar NPN-type primarily intended for application such as AC derives for motor, control system, inverters etc. It is housed in a heumatic ceramic on plastic package.
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- **16 channel Microprocessor based process controller**: It provides independent 4-20 mA signal for controlling up to 16 process parameter and has the capability to display process parameter control signal in the form of 20 LED bar graph. It also includes the features like auto/manual operation, modular packaging and reliability.
- **Process control deviation indicator**: It is very useful since it can be used by unskilled laborers, easy to install near manual control valve. It displays the process parameter deviation accurately. It has low cost, reliable and rugged design and requires less power (4-20 mA).

Technical Capabilities and Services to the Industry

CEERI is a research organization backed up by a solid foundation in design and process capability, an in-depth expertise, facilities and infrastructure at par with the international Hi-Tech status. The institute offers a complete spectrum of services to microelectronic power device industry. Major guidelines followed at the centre are:

- Consultancy service to entrepreneurs for setting up of semiconductor plants, wafer diffusion and standardizing the process line. They lend a strong experience to your investment in process development.
- Training of personnel in microelectronic fabrication technique.
- Transfer of know-how on devices such as power Darlington transistor, thyristors, rectifiers, p-i-n diodes and horizontal deflection transistor.

- Joint development program and sponsored research for:
    - Development of custom defined devices (both design and fabrication) as requested by consumer industry, professional electronics and defense.
    - Solving specific problems encountered by industry.
    - Further technological advancements required by industry to keep abreast of the state of the art design methodology and process innovations.

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Fabrication of power devices involves a large number of critical steps. Above all on demand institute offers facility or individual package as Ga/Al diffusion, double side photo masking etc. Institute also offers high tech courses and personnel training to entrepreneurs in the field of power semiconductor devices. The complete design and fabrication facilities has been developed at CEERI featuring

- Computer Aided device design: CAD facility is equipped with BIPOLE program using Ebbers, Moll, Gummel Poon models, circuit simulator SPICE, thermal WATAND program.
- High voltage deep junction diffusion technology
- Pyrogenic oxidation system.
- Surface field control techniques, spin etching and passivation.
- Double side mask alignment
- Large area element alloying
- In process test and junction evaluation methods
- DC and AC electrical measurements.

The existing facility can handle wafers up to 4" in diameter.

Robotics Projects in CEERI, New Delhi

- Voice operated wheelchair
- Computer controlled gripper for light weight objects
- Computer controlled arm for provision to attach components as end-effectors
- Voice operated automatic spoon-feeding machine
- Myoelectric arm for Prosthesis

Introduction

The first step to design anything is to realize completely what one is trying to design. Humans, as has been said, are one of the most complex machines known. Of the human body, definitely the most intricate and versatile is the hand. It is able to efficiently grip the softest and most delicate of objects, and also heavy and hard objects. The variety of objects which can easily be handled by the human hand is countless. Plucking a white hair, from a head full of black, or to bend a long iron rod, is all done by the human hand.

Though one of the most dexterous, it is also underutilized, as a machine. Thus, if we analyze our hand, we can easily exclude most of the unused components from the hand, and still make sure we do not lose the utility.

The study of robotic hands has been the foremost in the robotic science. Robotic arms, with a gripping end-effector, have been in production for a long time. Robotic hands which are anthropomorphic in nature have also been under research in universities for a long time. Stanford/JPL hand and Utah/MIT hand attempt to do this. The Stanford hand has 9 DOFs while the MIT hand has 16 DOFs. They also resemble the human hand in shape and size. A hand developed by DLR (Deutches zentrum fur Luft-und Raumfahrt) has four fingers with sensors, with twelve DOFs in total. The Robonaut hand developed by the NASA Johnson Space Centre has total of fourteen DOFs. The most advanced robotic hand built till now is the Shadow Hand, built by the Shadow Robot Company. It uses pneumatic “muscles” to incorporate 24 DOFs in their robotic hand, which is as much as the human hand. These all have one thing in common. They attempt to resemble the human hand in shape and size, and utility.

But for such hands to be used in prosthesis, more factors come into play.

Firstly, even after keeping in mind the size and shape, most complex grippers fail when weight is considered. Prosthetic hands should allow the user to comfortably carry it around, and should not strain the shoulder. Lightweight, therefore, begs for reducing the mechanical complexities of the hand.

Secondly, the number of signals available to the prosthetic hand is very less. Today, there are four common types of prosthetic hands. The first is the pure cosmetic hand, which allows poor, or no functionality. There are body-powered hands, which take their signals from the gross movement of a particular part of the body, usually the shoulder. Thirdly, there are myoelectric hands, which use the electromyographic (EMG) signals to decide movement. Lastly, there is a hybrid version of the prosthetic hand, which combines body-powered and myoelectric hand. Thus it is evident that the signals available to the robotic hand are very less in number, and the design should be such that the hand should carry out complex gripping tasks without any more instructions from the user.

Thirdly, the hand has to be portable, and the complete control unit, along with power sources has to be fitted into it.

Lastly, the prosthetic hand should be affordable to most of the handicapped people.

These reasons cause the traditional robotic hands to fail, and research has been going on in parallel to develop prosthetic hands which are comfortable, economical and provide good utility. Currently, most of the prosthetic grippers have only one DOF, the most advanced of which is the myoelectric hand available from OttoBock (SUVA). Research is being going on to try and control multiple DOF hands (up to four) by combining myoelectric signals available fom two different portions of the body (the Losh hand and the NTU hand).

In our design, we have attempted to design a robotic hand which can grasp effectively a wide variety of objects, using only two active DOFs in total. It should also be able to grip it as tightly as required and enable user to carry the object around. It should be light enough to be easily attached to the user's arm. It should be fast enough to look natural. It should automatically adapt itself to the shape and weight of the object, as it changes, without any other signals from the user. It should use myoelectric signals, as opposed to body powered prosthesis, since they are more comfortable. It should resemble the human hand in size and shape. It should incorporate in itself the necessary power source.

With these aims clear in the mind, the robotic hand was designed.

Main Control Diagram

This section describes in brief the control design of the hand. It only gives a brief outline of the functioning of the hand, with emphasis only on the electronic control circuits required for the hand. The diagram is given in Figure 1.

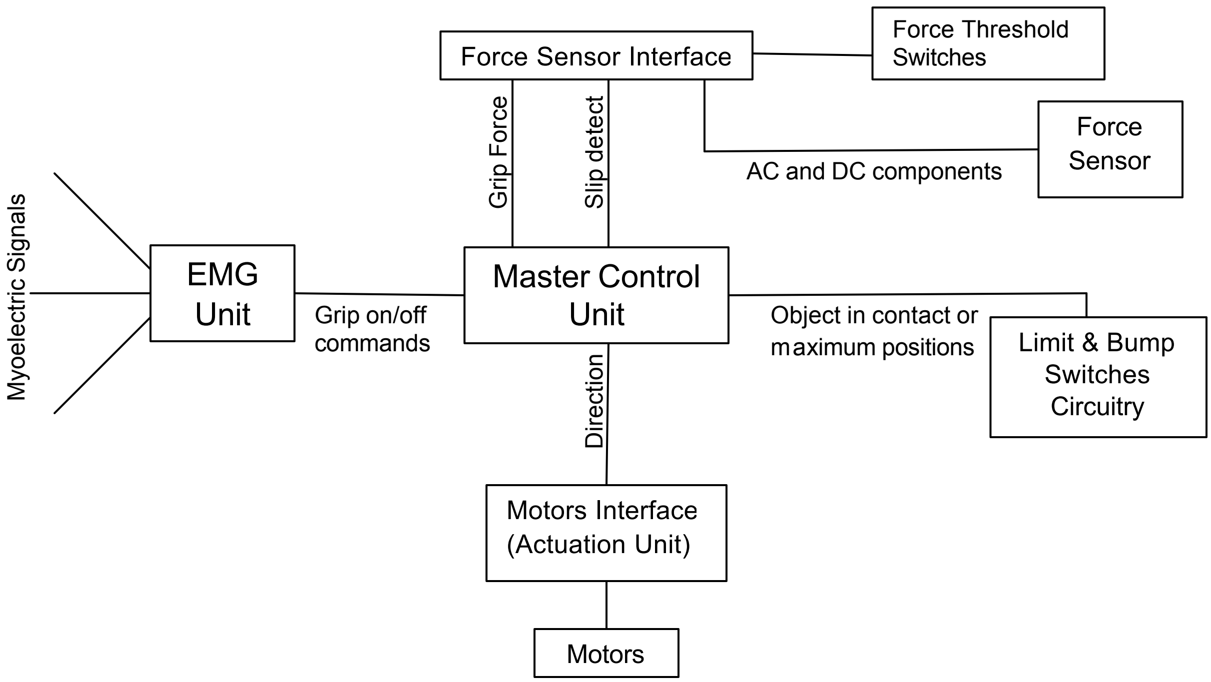


Figure 1: Main Control Block Diagram of the Hand

The design can be divided into the following sub-systems. By dividing them in this way, the control steps can be recognized more easily. A brief description of each system follows:

EMG Unit: This unit interfaces the master control unit with the user. This contains the myoelectric electrodes interface, along with pattern recognition code. This code is for the extraction of user commands from the myoelectric signals. It sends a grip on/off command to the master control unit.

Force Unit This unit interfaces the force sensors and the force threshold switches to the master control unit. They have code to detect slip, take gripping force as feedback, decide gripping action according to the force threshold switches, and send required data to master control unit. The master unit, according to other inputs, decides if the gripper should be actuated.

Limit & Bump Switches Unit: This unit detects two very important situations, which, if left undetected and untended to, can lead to major physical damages to the hand. First is when the hand has grasped the object completely, which triggers of the bump switches circuit. If, some or all, fingers have instead, reached their maximum positions, then also a signal is sent to the master control unit. This helps the unit stop the actuation to prevent damage to the hand.

Actuation Unit: This unit controls the actual movement of the hand, according to the signals from the master control unit. This unit is interfaced to two motors, which control each of the two degrees of freedom.

Each of these units is explained further in the following pages.

EMG Signal Analysis

To obtain the input from the use of the prosthetic hand, there are two basic methods of input, the body-powered and electrically controlled.

Body powered prosthesis is rudimentary and consists of mechanical switches which operate when certain parts and organs of the body move. For e.g. the elbow prosthesis is sometimes controlled by the shoulder muscles. Body powered prosthesis consists of a complex structure of straps and pulley attached to the artificial limb and the body.

Thus, by realizing the obvious discomfort to the user the body-powered prosthesis provides, it is recommended to use electrically controlled prosthesis. Before electrically controlled prosthesis is explained in detail, the advantages of electrically controlled prosthesis over body-powered shall be enumerated.

- Most importantly, it is the most painless and comfortable option for the user, when compared with body-powered prosthesis. The only contact with the user is the pair (or three) of electrodes, with a very small surface area.
- Though initially installation (and training) is cumbersome and time-consuming, but provided good care is taken, electrically controlled prosthesis is almost flawless is deciding what the user wants to do. It is also very long lasting, since it is fully circuitry dependent. Body-powered prosthesis requires straps and cables, which do lose their elasticity and other properties with use.
- It is light and small in size, when compared to the mechanical components required by body-powered prosthesis. Thus it is ideal for prosthesis, where miniaturization is very important.
- It reduces the *phantom limb pain* over time, which is the pain associated with amputated limbs. This phenomenon may be caused by confusion of brain hence it disappears when the brain recognizes the hand / arm not to be. Thus it actually helps the user overcome the pain of an amputated arm.
- It can easily be interfaced with a microcontroller which controls the actuation unit.

Electrically-controlled prosthesis can be further divided into three more types of control.

- **Vibration Electrodes**: In this technique vibration sensors are placed on the surface of the amputation. When the user wants to move the artificial limb, the muscles of the amputation move slightly. This muscle "vibration" is detected by the sensors, and the signal is carried to the actuation controller. This is the cheapest of the electrically controlled prosthesis since vibration sensors are available very easily. Also, comparatively, it requires least placement precision. The main disadvantage of this type of control is that the sensors are highly sensitive to vibrations and may pick external vibrations which had not been the intentions of the user. Also, slight displacement of the sensors may lead to them not functioning effectively.
- **Electromyogram Signals**: Electromyogram is convolutions of electric potentials propagating on muscle fibers, and can be detected on the skin surface. Surface electrodes embedded in the prosthesis socket make contact with the skin and detect and amplify muscle action potentials from voluntarily contracting muscle in the residual limb. These signals are amplified, and from them the relevant data is extracted to be sent to the prosthetic device controller (or straight to motors). This control is relatively much more efficient in correctly predicting the user's intention assuming the intelligence is trained properly. Though this method is more expensive than the previous one, it is still the more commonly used one due to its efficiency.
- **Electroneurogram Signals**: In this technique, attempt is made to decipher the signals coming from the brain of the human by placing probes on nerve ends or on the head. This method, if implemented effectively, can predict the user's action to perfection. Unfortunately, it is the research phase (as of publishing) and would be too expensive of the objective anyway.

Thus by going through the various options, electromyogram (EMG or myoelectric) signals have been decided to be used in the prosthetic hand. EMG consists of two main parts, the electrodes, and the EMG analysis. These electrodes are available widely for their widespread use in chiropractic analysis. A suitable electrode for our purpose is available with the Motion Lab Systems Inc. It is small, DC-coupled and includes pre-amplifier circuitry. The details of the electrode are given in the appendix.

The extraction of data from the electric signals (from the electrode) is also very important to decide what the user intends. To achieve this, there are lots of techniques of pattern recognition currently being employed. Some of them include Genetic Algorithms, Hidden Markov Models, Neural Networks, Fuzzy Systems, etc. These methods require a training period for the algorithm to learn the user's responses, and aligned itself to the user.

Each user using myoelectric prosthesis has to undergo a pre-prosthetic training regime. This training includes a couple of steps. First, the placement of electrodes has to be decided. Since we have only an on/off gripping action, it is advisable to use one electrode as a toggle switch. Another electrode will be used as a reference electrode. These electrodes can be placed at enough distance from each other, along different muscle lines. In the electrode selected for our purpose, both electrodes are available on the same unit (see appendix).

Along with the placement of electrodes, a comfortable prosthetic socket has to be designed, based on the level of amputation. Then the user has to undergo a training session in which his responses are associated with intended action by feature extraction using any of the above mentioned techniques. In higher level prosthesis, this step is very time-consuming and irritating for the user, but in our case, since, there is only one response to be monitored, it is a much quicker process. Care should be taken to make sure nearby muscle contraction/expansion does not result in a wrong inference. Electrode should be protected from sweat, and movement.

After the training period, the microcontroller of the EMG unit has to be programmed to recognize the change in myoelectric potential, and send signals to the master microcontroller to carry out the required task. If additional circuitry is required before the microcontroller stage (like filters, etc.), it also should be fabricated. Thus myoelectric prosthesis can be incorporated for the hand.

I have not gone into the details of myoelectric prosthesis and the associated circuits. The circuits vary from user to user and a common (or "generic") circuit cannot be drawn. Myoelectric has been in use for prosthesis successfully for some time and is a very common option now.

Mechanical Design

This section describes in detail the mechanical design of the hand, and the way in which it attempts to achieve a flexible and reliable grip by using only two active degrees of freedom. Initially the structure of the hand is explained, and then the actuation unit is studied in detail to show the grasping and gripping of objects of variable shape and size.

Overview

The hand consists of four fingers and a thumb. The thumb and the little finger have one degree of freedom each, while the rest three fingers can be said to possess two degrees of freedom. In total there are two active degrees of freedom. All fingers share one *main* degree of freedom, the joint of which is at the base of each finger. The second degree of freedom is shared by the three middle fingers, called *tips* degree of freedom. The approximate location of joints for smooth gripping is shown in Fig. 2.

As seen in the figure, the hand also consists of a number of bump switches (seven). These switches are tactile sensors which get switched on when they come in contact which any external object. They shall be explained in detail later in the text.

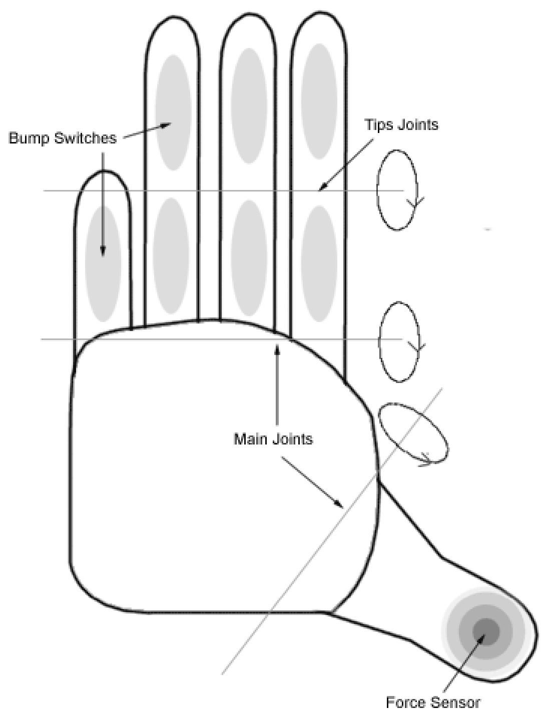


Figure 2: Overview of the hand showing joints and the placement of sensor and switches

The thumb consists of a force sensor, which senses the total force acting on the thumb. It is used in feedback to adjust the gripping force for a best grip. It has been also used to detect slippage, if any, between the object and the hand. The design requires the force sensor to cover as much area as possible, for efficient functioning.

Before going into the details of the grasping and gripping action, I would like to mention that even though the hand has 2 active degrees of freedom, and many driven ones, it can only have a cylindrical grip (as used when lifting a glass). Other grips were not explored since they are not used very often. The design is so that it will be very difficult to incorporate other grips, while still attempting to preserve the simplicity and novelty of the design.

Finger Design

Before the details of the grasping and gripping action can be studied, it is important to study the construction of the finger. The figures 4 & 5 show the design of the fingers and the joints.

The finger shall work on the principle of control strings, i.e. each joint in the finger will be connected to the actuation unit by a string, which shall control the angle of the joint. The string design in our hand shall be one way, and pulling on it shall bend the joint. Thus a circular spring, with a low spring constant, will have to be attached to each joint to pull the string back and to re-orient the joint (not shown in figure).

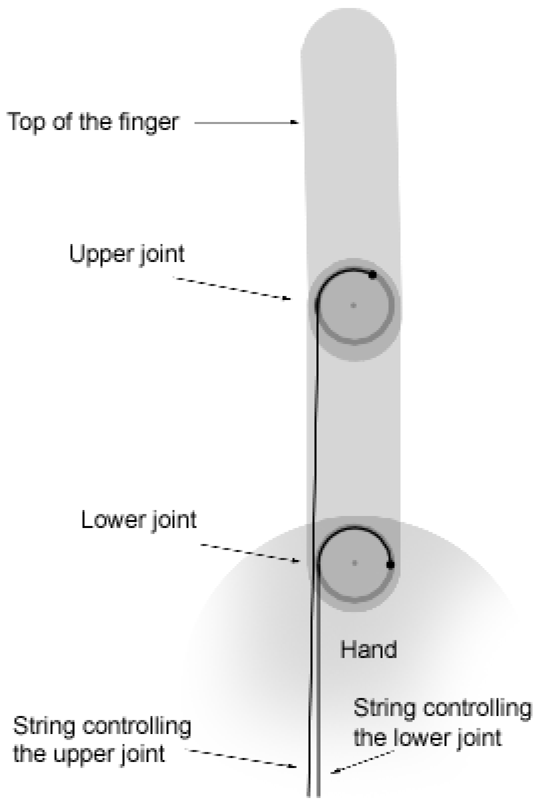


Figure 3: Unbent finger with joints and strings

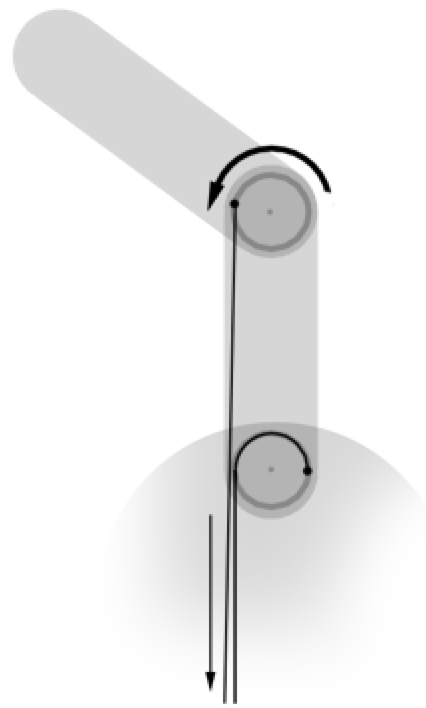


Figure 4: Finger with top of the finger bent

Appropriate pulley design has to be incorporated to make sure the control strings do not get entangled or come in contact with each other.

The material used to make the finger has to be light and durable. For this purpose, it was decided to use hard plastic or hollow metal. The finger will not contain much circuitry in itself, and thus almost all of the volume occupied by the finger can be taken up by the material.

The finger has been designed such that even if it is later decided to independently control each finger (by giving them individual actuation), it can be easily incorporated. Each finger has a number of strings (one for thumb and little finger, two for middle fingers) coming out, which control the joint angle. These strings from each finger can go into different actuation units, or the same one, according to the design of the rest of the hand.

Before explaining the working of the hand further, one point may be mentioned, which is the difference between grasping and gripping. Grasping, in this text, has been used as the action by which fingers are placed around the object, as if to hold it, but to exert less or negligible force. Gripping on the other hand, assumes grasping, and is the correct exertion of grip to hold the object in air steadily against gravity. Thus gripping requires application of force by the fingers in correct quantity, to ensure no slippage or crushing takes place. With these differences clear, the design of the hand can be proceeded with.

Grasping

To understand the grasping requirement, figure 5 is given. It shows the diagram of the actuation unit if only grasping was required from the hand, for three fingers. It is same as the diagram for the tips actuation unit since the tips actuation unit only requires grasping action from three fingers. It consists of the rough shaded solid container (actuated unit), having three cylindrical holes, to accommodate three pistons, with the associated string attached to the pistons. The end of the tube has a spring fixed onto the actuated unit and the piston. These springs have a very low spring constant.

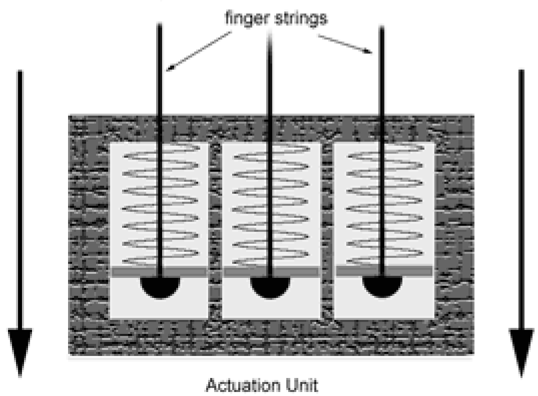


Figure 5: Tips Actuation unit

When actuated, the unit moves in the direction of the big arrows. This also forces the strings to get pulled also, and the fingers start bending. This goes on till one of the fingers touches the object. This means the finger cannot move forward anymore. If the unit is actuated more (as it will be) the spring of the corresponding finger starts compressing easily (since the spring has a low spring constant). This ensures the pressed finger remains stationary without exerting considerable force on the object, while the other fingers continue to bend.

This process continues till another finger comes in contact with the object. The corresponding spring also starts compressing, exerting a negligible force on the object, while still letting the third finger bend more. This continues till either all of them touch the object, or have reached their maximum positions.

In this way, using the figure, it can be understood how the grasping of a three finger hand following this design works. Using only one actuation direction, the design controls three fingers in such a way that only the required ones bend till they come in contact with the object. It exhibits efficient grasping of objects of a wide variety of shapes and size.

This method of grasping will be explained further after the gripping action has been described. This is so that the total actuation unit of the hand has been presented, and descriptions of grasping and gripping can be given using the actual design of the hand with all fingers, not with only three fingers, as described above.

Gripping

To incorporate gripping, first step was to assign the above grasping mechanism to all four fingers. The thumb is directly attached to the actuation unit since it provides reaction force. The three middle fingers (the ones mainly used for grasping) had another set of springs attached to them, with a much higher spring constant. These springs are termed *gripping* springs. The little finger also has a set of these springs, though it does not have grasping spring. When grasping is taking place, there is negligible compression of the gripping springs due to their high spring constant. By the end of the grasping process, the grasping springs are compressed according to the shape of the object to be held.

When gripping action starts, the position of fingers is not supposed to change, only more force has to be applied. As the actuation moves further, the grasping springs get further compressed, applying a tiny amount of force. If this force is enough to grip an object the gripping springs need not come into action. If it isn't, then, after the grasping springs are fully compressed, the gripping springs start getting compressed. This results in a larger amount of force being applied to the object, resulting in a strong gripping action. The actuation keeps moving till the slipping action stops, signifying the end of gripping action.

The figure shows the springs and the piston arrangement as described above.

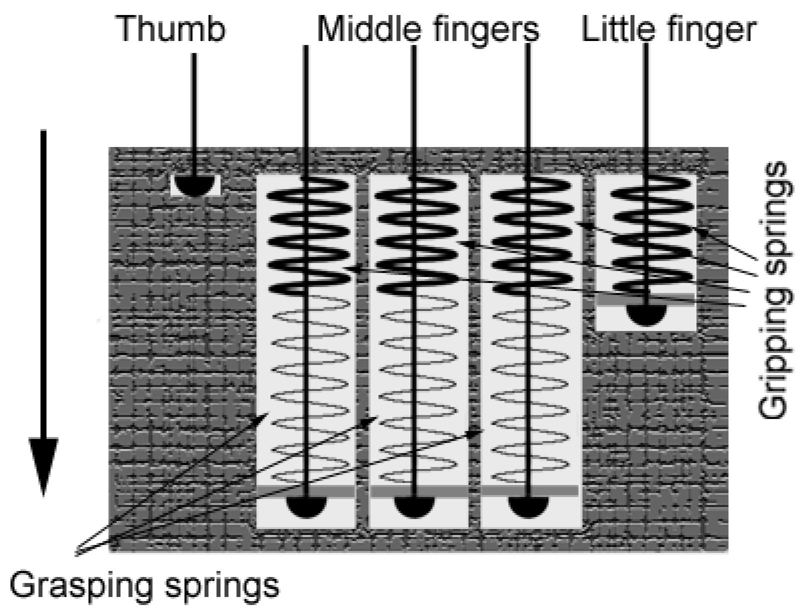


Figure 6: Cross section diagram of the actuation unit of the hand showing the corresponding springs and strings for each of the five fingers.

Actuation Unit

This section will describe further considerations to keep in mind when fabricating the actuation unit, and will talk about the materials of each component.

The sensitivity of the finger joints has to be high, i.e. for a small extension of the control string, the joint should bend by a large angle. This is so that small linear range of the actuation unit shall cover the whole of the sweep of the finger joints, thus saving on the space. Thus appropriate pulley/gear mechanism should be included in the fingers to achieve this. It should also be made sure that a small change in linear displacement of the actuation unit also corresponds to large change in the applied force, for the same reason.

This would mean that the actuation unit shall not be moving large distances. Thus it has to be connected to the motor in such a way that the joint angles and the force are still controllable, without sacrificing speed. For example, if the motor is a stepper motor of 360 steps/revolution then each step should not correspond large angle and/or force changes, and nor should one whole revolution correspond to a small change in angle or force, since that would reduce the speed of operation.

The finger tips actuation unit does not require very high torque, so the corresponding motor can be a low power dc motor. The finger actuation unit, o the other hand, since it shall be applying the force, required a higher torque motor. Thus a high torque dc or stepper motor can be used. Appropriate controller ICs shall have to be selected (appendix).

There are three types of springs being used in the hand. Firstly, the circular springs in the finger joints are to bring back the finger to initial position. Since they have to overcome friction only, they are low-force springs. The grasping springs (in both tips and the finger actuation unit) should have spring constants slightly higher than that of the circular springs. They should not be too strong because then high force will be applied to the grasped object during grasping, which might break the object. The gripping springs should be much high spring constant springs to enable the whole range of force to be applied from the small linear range of the actuation unit.

The actuation units can be constructed with any hard, light and durable material, like aluminum, hard plastic. Surface should have the least friction possible. The length of the springs in each compartment has to be calculated using the spring constants and the angle and force ranges. Care should be taken so that at initial position, all fingers are straight open. Also, as each actuation unit moves, the fingers should bend together, at the same speed, and should reach the maximum position together.

The strings have to be inextensible, strong and durable. Thus for the strings the obvious choice would be to use nylon.

Switches & Sensors

This section describes various sensors and switches in the hand, the way they are connected and the role they play in detecting various events.

Bump Switches

The placement of these switches is shown in figure 2. These are tactile switches which get switched on when there is a slight contact with the switch. These switches are to detect when all the fingers are in contact of the object, at which point the actuation has to stop and end the grasping phase. They are highly sensitive mechanical switches, and thus the master microcontroller should include a debouncing routine to overcome vibrations, etc. Though the switches themselves may be small, the covering area of the switch has to be comparatively large, each bump switch covering at least half of a finger. The switch should withstand frequent use without degrading in quality. Such switches are widely available in the market, so there is no need to dwell further into the topic.

For nomenclatures sake, a bump switch on the upper half of the *n*th finger shall be signified by *Bum(n, upp)* while the bump switch on the lower half shall be signified by *Bum(n, low)*.

Limit Switches

Limit switches are those switches which close when any moving part reaches either part of the motion range. There are two types of limit switches in the design of the robotic hand.

The first type of limit switches are angle switches. At each of the finger joints of the hand, an angle switch will be placed to detect when the finger has reached the maximum bent position. For small or very extremely shaped objects, some of the fingers may not get in contact at all. The limit switches shall help detect these instances and ask the master microcontroller to stop actuation to prevent damage to the finger joints and the actuation units. These switches can also be signified by a similar method, for e.g. *Lim (n, upp)* and *Lim (n, low)*.

The second type of limit switches is ones which shall detect the minimum and maximum position of the actuation unit. The minimum position corresponds to the initial “open” position of the hand, and the master microcontroller shall have to use this signal to detect this position whenever it has to return the hand to initial position. The maximum limit switch shall detect the maximum position of the actuation unit, which corresponds to the fingers bent at max angle and also exerting the maximum possible force. This position is never bound to happen, unless there is no object and the user sends a gripping signal. By keeping this switch, however, the master controller shall avoid damage to the fingers and actuation unit in the unlikely event of the actuation unit reaching maximum positions. These switches can be called *Lim (max, upp)* or *Lim (min, low)*.

These switches shall also require debouncing sub-routines as in bump switches for effective handling of these extreme situations.

Force Sensor

Force sensor is one of the most important components of the hand. It is the sensor which shall detect the amount of force being applied to the thumb, or alternatively, the total force being applied by the other fingers on the object. It is placed on the thumb as shown in figure 2. There are two types of signals which shall be obtained from the sensor.

The first type of the signal is the low pass filtered low frequency signal obtained from the sensor. This signal corresponds to the total weight being applied to the sensor, and hence the object. This analog signal is sent to the force microcontroller ADC which calculates the amount of force being applied, and compares it to the threshold level set. Accordingly the master microcontroller releases the grip.

The second type of the signal is the high pass filtered high frequency signal obtained from the sensor. When an object starts slipping from the grip, then due to friction, the force on the sensor contains lots of spikes and vibrations. Thus if this signal is high pass filtered, we shall obtain a slip signal. This analog signal is sent to the comparator in the force microcontroller, which, according to the preset threshold level, sends a slip detect signal to the master microcontroller, which tightens the grip till the slip detect signal goes down.

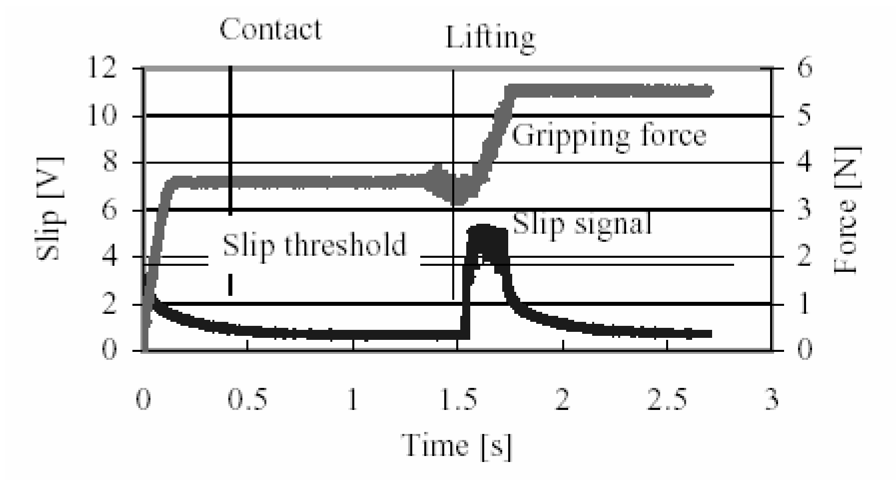


Figure 7: Slip detection and corresponding correction
(Ref: "Versatile End Effector Control for Stationary and Mobile Manipulator Platforms"; Friedrich, Lim and Nicholls)

The above graph shows this process taking place in a manipulator in Industrial Research Ltd, Aukland. Just when the object is lifted, the slippage starts, the slip signal crosses the slip threshold and hence the gripping force is increased. This leads to the object getting gripped firmly and the slip signal goes down again. We intend to obtain similar graphs during our testing stages.

The force sensor should have a linear range for the maximum force range which has been decided. For such a large force range, it is advisable to use a semi-conductor force sensor available in the market since it will be more resilient to external conditions, than strain gauges. Though much more expensive than strain gauges, for such an important component of the hand, we have decide to prefer quality over price. The semi-conductor force sensor still requires the low pass filters and high pass filters.

Force threshold switches

These switches are manual switches which help set the maximum force level for the force microcontroller. There are four levels of thresholds which the user can decide between. Suppose the user has to lift eggs. In this case, force should not be applied till the eggs slips since it may break. But suppose the user has to lift a heavier object, like a book, it will be advisable to apply some force (since there is no danger of slipping) and apply more force only if slippage occurs. Thus according to the threshold levels, the force microcontroller can decide how much force to apply in the grasping stage itself, and what is the maximum force that should be applied to the object. Though the hand can work without the levels (or if the user sets wrong levels), it work more efficiently if the levels are set correctly.

Connection of Switches

After describing the placement and importance of the different types of switches, it is imperative to explain the electrical connections and the interfacing to the microcontrollers. The maximum and minimum limit switches of the actuation units are simple high enabled switches which can have a simple circuit as shown in figure 8.

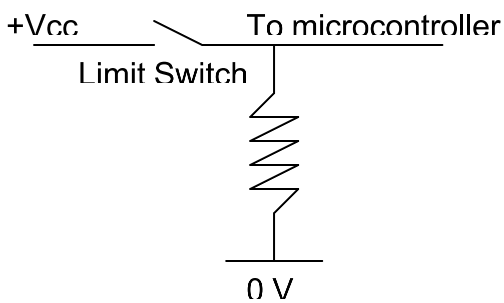


Figure 8: Connection of maximum and minimum limit switches of the actuation units

When we talk about the bump and limit switches of the fingers, the circuits get a little complicated. For each finger, either it should touch the object or it should reach the max bent position for grasping. Thus for each finger the bump switch and the limit switch have an OR relationship between them. Also, the whole grasping process will only be finished when all the fingers are either touching the object or are in their maximum positions. Thus between fingers there exists an AND relationship. This leads us to design the following two circuits for the tips and for the fingers (figure 9 & 10).

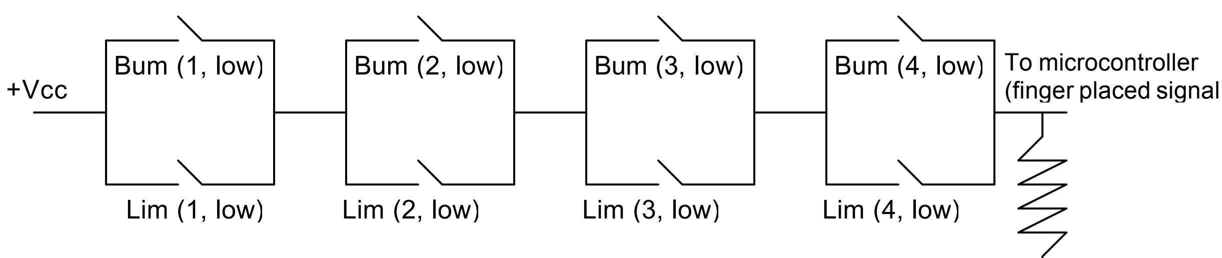


Figure 9: Connection of switches for the lower parts of the fingers

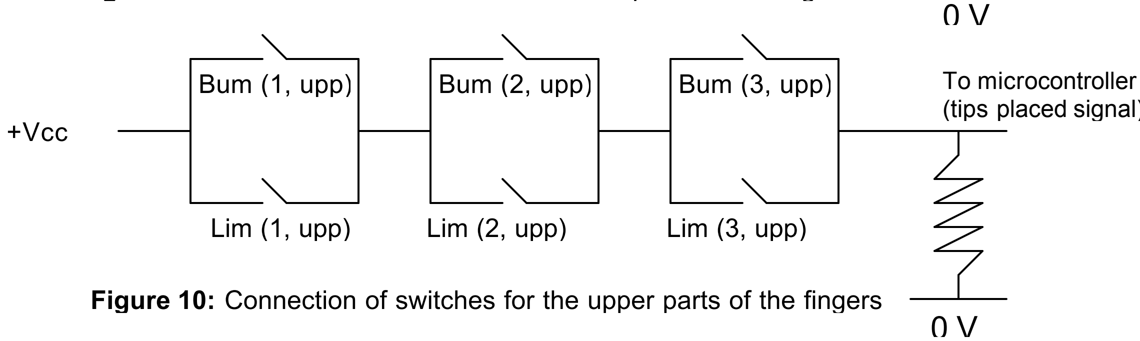


Figure 10: Connection of switches for the upper parts of the fingers

Working

This section shall explain with diagrams the different steps taken for grasping and gripping objects by the robotics hand.

Before we begin with the explanation, in further diagrams, we will be representing the hand according to its expected contact points, i.e. points where the bump switches are placed. The upper bump switches are represented by dark circles while the lower ones (and the thumb) by light circles. Figure 11 shows these circles as on top of the hand. Henceforth, the figures shall not contain the outline of the fingers.

As the first example, we shall take a simple cylindrical object. At initial position, the fingers are open and the actuation units are as shown in figure 12.

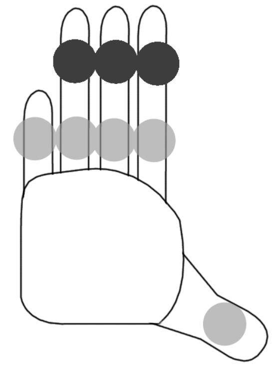
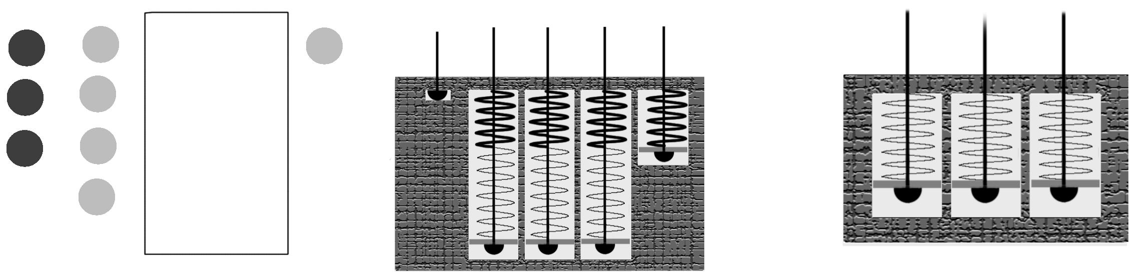


Figure 11: Hand Representation

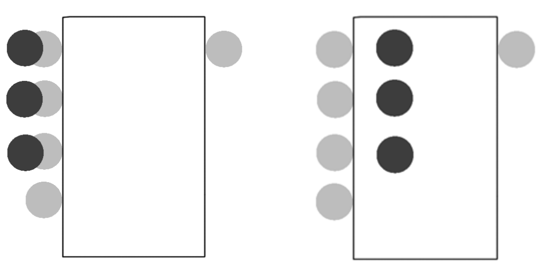


(a) (b) (c)

Figure 12: Initial Positions – *Initially the fingers are all open, as shown in (a) which is the side view of the object and the hand. All springs are uncompressed for both the finger actuation unit (b) and the tips actuation unit (c).*

The thumb is placed against the object and the grasping starts. First the finger actuation unit is moved, till the finger placed signal is obtained. Then the tips actuation unit is moved till the tips placed signal is received. This ends the grasping phase. For this particular object the springs shall remain uncompressed till the end of grasping phase, i.e. same as initial the position (Fig 12b & 12c). The finger positions are shown in figures 13a and 13b.

After grasping of the cylindrical object is done, it is lifted. If slippage occurs, then gripping action comes into focus, by moving the fingers actuation unit until the slippage stops. First the grasping springs get compressed, which were uncompressed in our example, and then the gripping springs if slippage hasn't stopped. Since all fingers are placed along the same line, the compression of the gripping springs also equal.



(a) (b)

Figure 13: Grasping of Cylindrical object -
In (a) the finger actuation unit has been moved appropriately, showing the lower halves of the fingers to be placed, but the upper halves are parallel to the surface of the cylinder. In (b) the tips actuation unit has been moved to place the upper halves firmly on the cylinder.

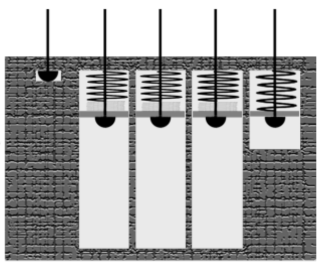


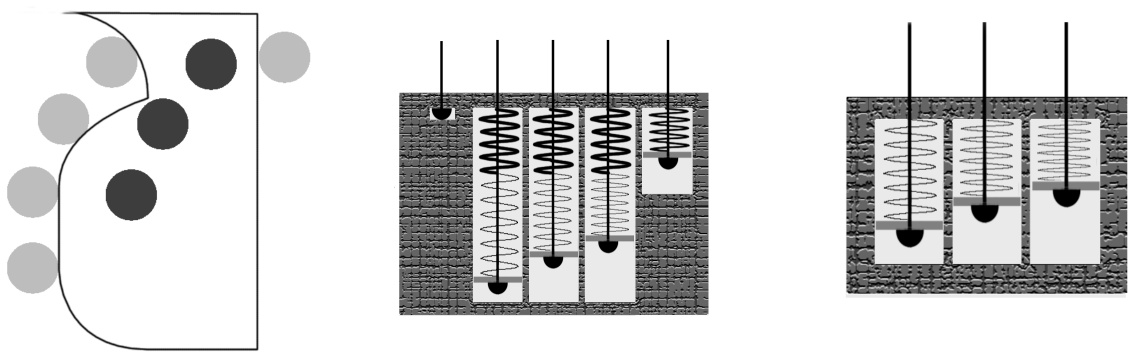
Figure 14: Finger Actuation Unit *Shows the finger actuation unit during tight gripping. Though in this case the little finger's piston Is in the same position as others, it'll usually not be the case*

In Figure 14 the status of the springs in the finger actuation unit is shown at one point of time during the gripping stage. In the figure the gripping is very tight, as can be seen by the excessive compression of the gripping springs. For this stage to occur in actual operation, the force threshold will have to be the highest. Also, since the little finger does not have a grasping spring, the compression in the gripping spring will be slightly less than in other three fingers.

The tips actuation unit, along with the finger placement remains unaltered during this phase, and hence is not shown.

As our next example, we shall take a vaguely shaped object. Though object has a plain straight side towards the thumb, for gripping, that side is not very important.

As grasping starts, this time the fingers shall be placed at different positions along the surface of the object. The index finger will go the furthest, followed by the middle finger. The third finger and the little finger shall stop the earliest. In this case, the gripping spring of the little finger may get compressed a little. A similar situation will exist for the tips actuation unit, but only for the three fingers. Thus after the grasping stage, the finger placement along the second object will be as follows.



(a) **(b)** **(c)**

Figure 15: Grasping of random shaped object- *The object will be grasped as shown in (a). The finger actuation unit contains different compressions for different fingers (b). A similar pattern of compression exists for the tips actuation unit (c) for the corresponding fingers.*

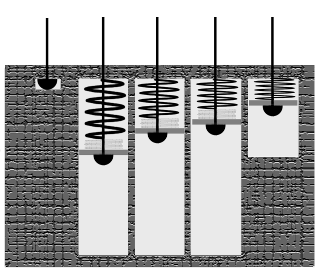


Figure 16: Gripping of random shaped object- *It is evident that the pistons correspond to the ones in grasping.*

During the gripping phase, after the grasping springs have compressed, the gripping springs will start compressing. Thus gripping springs for the third finger may start compressing before that of index or middle finger. Thus more force will be applied by the third and the little finger than the others, which, as observable, will be required for a good grip. Again the finger actuation unit is shown in the figure since the tips actuation unit and the finger placement does not change during this stage.

This is how the hand is capable of handling various shapes of the objects. For proper working, it should be made sure the microcontroller detects slippage and acts upon it as fast as possible.

Microcontrollers

This section describes the process of selecting and using the microcontroller.

Requirements

If we refer to the basic block diagram (*Page 9*), then we can directly observe the requirements needed for each of the microcontroller. The aim has been to minimize the number of microcontrollers, while still maintaining a modular approach to design. Thus microcontrollers are used so as to minimize power usage, and to maximize the feature utilization and compatibility of the microcontrollers.

EMG Signals Unit

Analog Inputs	2	*from myoelectric electrodes*
Digital Inputs	0	
Digital Outputs	2	*for grip command*
Memory	High	*for myoelectric signal lookup tables*

Actuation Unit

Analog Inputs	0	
Digital Inputs	3	*for grip control (from master microcontroller)*
Digital Outputs	4	*2 pins for each motor (since bidirectional)*
Memory	Low	*only a small lookup table*

Force Sensor Interface

Analog Inputs	2	*for Low Pass Filtered (DC) & High Pass Filtered (AC)*
Digital Inputs	2	*from Force threshold switches*
Digital Outputs	1	*for Slip detect LED*
	X	*for communication with the master microcontroller*
Memory	Low	*only a small lookup table*

Master Microcontroller

Analog Inputs	0	
Digital Inputs	2	*grip commands from EMG Signals unit*
	1	*bump and limit circuitry for fingers (finger placed signal)*
	1	*bump and limit circuitry for finger tips (tips placed signal)*
	2	*max limit switch (for 2 actuation units)*
	2	*min limit switch (for 2 actuation units)*
	X	*for communication with force sensor interface*
Digital Outputs	3	*for grip control to Actuation Unit*
Memory	High	*the control program will be stored here, with all procedures*

To reduce the number of microcontrollers, it was decided to combine the Master microcontroller with the force sensor interface. Thus a revised table of requirements can now be made by integrating the force sensor interface with the master microcontroller.

Unit Name	ADCs	Dig. Inputs	Dig. Outputs	Total I/O Pins	Memory Requirements
EMG Unit	2	0	2	4	High
Actuation Unit	0	3	4	7	Low
Master (+Force)	2	10	4	13	High

Selection

After the requirements had been listed, market was scanned for the various microcontrollers available for use. Out the various series currently available, the PIC series by Microchip, USA was found to be most suitable for our use. This was because:

1 RISC Architecture
2 Economical
3 FLASH Memory, less power consumption
4 Widely used, thus documentation easily available
5 Kits and Software easily available
6 Wide Range of features in each microcontroller
7 Availability in India

After a careful analysis of the range of PIC microcontrollers, the list of microcontrollers to be used is as in the table. It has been tried to utilize, to the maximum, all the available features of the microcontroller, so as to get a good value of money. Lack of availability may force usage of a different, but similar in features, microcontroller.

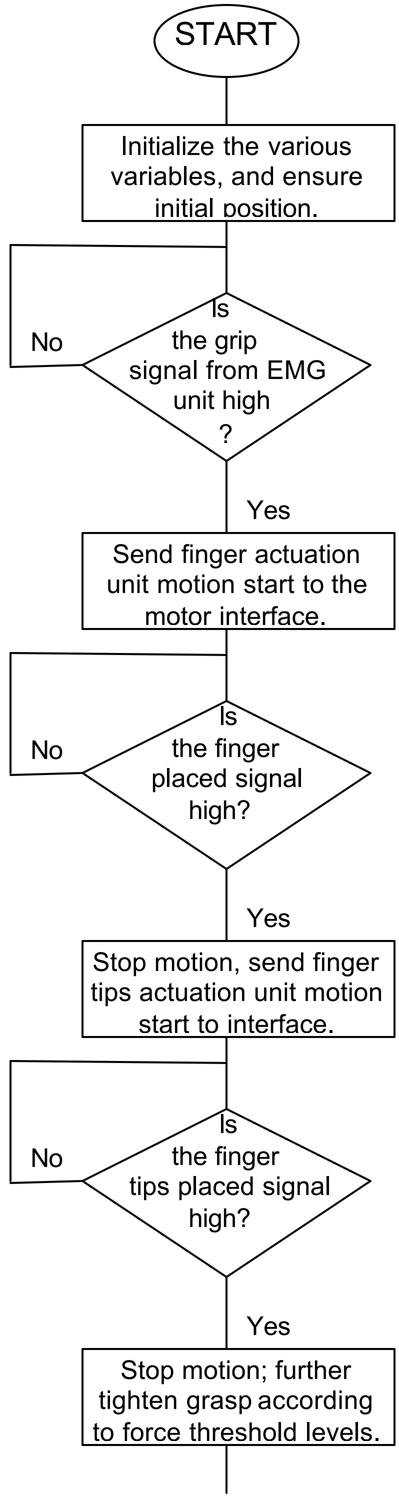
Unit Name	Microcontroller Number	Program Memory	RAM	Memory Words	ADCs	I/O Pins	Special Functions	Total Pins
EMG Unit	PIC12CE674	3584	128	2048x14	4x8bit	6	Low Voltage Detect	8
Actuation Unit	PIC12F67X	1792	64	1024x14	0	6	Low Voltage Detect	8
Master (+Force)	PIC16F873	8192 (FLASH)	192	4096x14	5x10bit	22	Sleep, FLASH	28

It may be noticed that even though the requirement for the actuation unit microcontroller had 7 I/O pins written, one with only 6 I/O pins can also be used if a two channel motor controller IC is used, for example BA6238A (from ROHM).

Thus, the microcontrollers have been selected and can be easily connected as in the block diagram, keeping in mind the various individual requirements for the microcontroller (like power sources, Reset control, etc.)

Flow Diagram of the Program

This is the approximate flow of the program which shall reside in the master microcontroller. Some more considerations and sub-routine descriptions are given after the diagram.



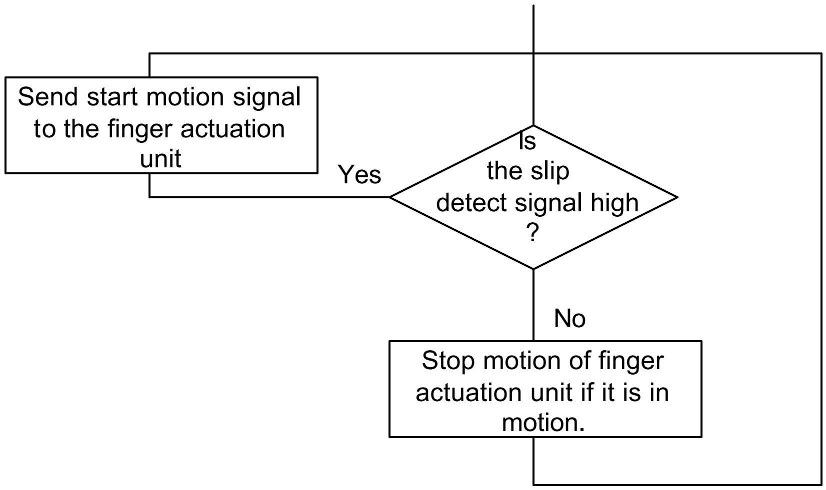


Figure 17: The basic flow diagram of the program for the master microcontroller

The above flow diagram does not contain many other considerations which shall be listed below.

- **Grip off signal:** This signal has not been included since it acts more like an interrupt. Whenever the EMG unit requests the master microcontroller to release grip, it should leave all current status, and should bring the hand back to the initial position.
- **Initial Position Sub-Routine:** This sub routine will request the actuation units (one after the other) to start reverse motion. When the corresponding Lim (min) signal goes high, it means the actuation unit is in the initial position. The microcontroller should then send a stop motion signal to the motor interface.
- **Grip Force Increase Sub-Routine:** This routine has to request the finger actuation unit to start and stop motion according keeping various signals in considerations, namely, force threshold level, DC signal from the sensor, and Lim (max) signal.
- **DC Signal from Force Sensor:** If this signal increases beyond the level set by the force threshold switches, then the master microcontroller should ask the motor interface to stop motion. After this the program should continue detecting slip since the user may change the force threshold level during the operation.
- **Lim (max) signal:** This signal detects when the actuation unit has reached the maximum position. At the reception of this signal, the microcontroller should stop motion of the actuation units and may go back to initial position. This event is rare, but if it occurs, it is likely to damage the hand very badly if this feature is not included in the software.
- **Debouncing:** Appropriate debouncing code with proper timing should be added before checking any of the analog signals, or the signals from mechanical switches. This shall prevent the microcontroller from detecting only proper events.

Keeping the above considerations in mind, the master microcontroller can be coded to efficiently perform its role.

Construction Steps

This section shall briefly outline the chronological steps required in fabricating the robotic hand. Some of these steps can be worked upon in parallel with each other, and whenever possible, should be done so.

- **Calculations:** Different parameters like the angle ranges for each joint, force ranges, actuation units' ranges, force threshold ranges, etc. should be finalized. Based on these, other parameters should be calculated, like the spring constants, the pulley/gear structures, finger joint structures, etc.
- **Frame:** The frame of the hand should be constructed from appropriate material, keeping in mind the approximate sizes of the actuation units, placement of motors, pulley/gear systems, etc. There will not be any electrical circuits on the hand; they shall be contained in the arm.
- **EMG I:** Myoelectric electrodes should be studied, and then should be interfaced with a computer with appropriate circuitry. Pattern recognition technique should be selected and software should be written onto the PC to correctly detect these signals.
- **Finger Construction:** The fingers should be constructed, with joints, limit & bump switches and strings. The two strings should independently control each joint, and an equal extension in string in two different fingers should correspond to equal bend of the finger joint. The sensitivity of the finger should be high.
- **Actuation Units:** The two actuation units, with springs and pistons, should be constructed and connected to the five springs. Appropriate limit switches should also be placed. At the end of this step, we should have a "manual" hand, i.e., by pulling and pushing the actuation units, the whole hand should operate as desired.
- **Motor Controllers:** The two motors should be connected to the motor controller ICs and to the motor microcontroller. Mcrocontroller should then be programmed to test the motor circuits. Motors should then be connected to the actuation units with gears.
- **Force sensor interface:** Using the appropriate AC and DC filters, signals should be connected to the CRO, and testing should be done by placing the sensor on the hand. Appropriate signals should be received on the CRO for slippage and force.
- **Master microcontroller:** The master microcontroller should be connected as required to the various signals and sub-systems, namely, bump & limit switches of tips and the fingers, force threshold switches, motor controller microcontroller, force circuitry, etc. The master microcontroller and the motor microcontroller should then be programmed to test the hand.
- **Testing I:** In this step the hand should be vigorously tested for grasping and gripping errors for a variety of objects. Any errors should be taken care of in this step only. At the end of this step, we should have a hand which can grip any object and operational by a switch.
- **EMG II:** Pattern recognition software should be programmed onto the microcontroller, and it should be connected to the master microcontroller. Before connecting to the master microcontroller it should be ensured the software does detect required EMG signals effectively.
- **Packaging:** The whole hand, along with the arm, should now be packaged and covered with appropriate material. The power supply should also be included in the arm.
- **Testing II:** This step requires further testing of the hand, now by attaching it to an amputee. This testing phase should especially keep in mind the safety and ease of use of the robotic limb to the user.

Thus by following these steps, the robotic arm can be constructed effectively.

Conclusion

This paper has described in detail a design for a Robotic hand for prosthesis. The problems faced by most of the prosthetic devices nowadays were first studied, and then requirements from the design were listed. Keeping the user in mind, the robotic hand was designed. This prosthetic hand provides various advantages over conventional prosthetic devices.

It includes a unique method of controlling five fingers using only two motors, in such a way that they can still grasp and grip objects of different shapes without requiring complex control. Two motors provide two active degrees of freedom to three middle fingers, while the spring action allows each finger to move independent of the other, if the grasp requires it. Thus the driven degrees of freedom adapt themselves to the object. The same grasping actuator is being used to grip more tightly also, again using the spring action to increase the force.

Another important advantage of the hand is that it is light. It does not have any heavy mechanical components to make it too heavy to be handled easily. Most of the weight shall be taken over by the power source and the motors, followed by the actuated blocks. The fingers and the body can be light plastic, with a rubber covering to increase object surface and finger surface friction.

Since it is designed to be myoelectrically controlled, with toggle switches, it is very comfortable for the user to control. Since only one action controls the gripping action, the user will not get confused about the actions in emergencies, and it is very unlikely that he will give a wrong command. The toggle switch technique also makes it a safer option that the normal two action control, since the user, even in situations of panic, can easily repeat action to open grip, instead of wondering which action corresponds to switching off.

It has been attempted to design the hand so that is works efficiently has long as possible. Thus components which need constant maintenance and replacement have not been used, and instead, though seemingly more expensive, more durable options have been used. This was another important reason why body powered prosthesis was not used when designing this hand.

The design has attempted to combine efficacy along with affordable price, without necessarily putting one in front of the other. Thus the hand has been designed with a more convincing gripping action, light and comfortable, and without unnecessary features which usually increase the price of conventionally available prosthetic devices.

The design in currently being implemented in the Robotics Division of the Central Electronic Engineering Research Institute (CEERI), New Delhi.

Future Incorporations

After the concretization of this design, there are further features which can be added to make the robotic hand more efficient and user friendly. Some of these features require advancements in technology used, thus increasing the price. Thus, they shall only be used if they are necessary.

The most important indicator of the efficiency of a robotic hand is the number of degrees of freedom. The hand, as designed, has two active DOFs, which drive four fingers and a thumb. If a third degree of freedom is decided to be added, the most obvious choice will be the wrist. This incorporation, electronically and mechanically will not cause much problem; it requires space of only one motor and will rotate up to 180 only. Thus the motor can easily fit in hand. The problem in adding another motor is the problem of controlling it. Another set of myoelectric signals will have to be read and deciphered, and either a proportional or a step mechanism will have to be used to control the wrist angle. This feature will help the user grip objects not easily graspable by a non-rotating wrist. Instead of the rotation, the extra DOF could be used in the bending of wrist.

Once the hand has been constructed successfully, effort can be made to integrate all the three microcontrollers into one larger microcontroller. This will help in many ways. Firstly, the size of the circuit will reduce by a huge amount, thus making the circuitry lighter and smaller. Secondly, much less power shall be consumed by one microcontroller, resulting in a longer battery backup. Integration would also obsolete the need for synchronization between microcontrollers, thus features like SLEEP will be easier to program.

We have not talked much about the power supply yet. This is because there is a huge variety of a power supply available in the market right now. One of them can be selected and used even in the later stages of construction. But after selection, circuits can be designed which can give the user information about the battery status, by a LED bar-graph, for example. There can also be charging and power on LEDs, along with a charging jack. Such features will increase the size and weight, thus are advised against is not useful, though a Low-Voltage indicator is necessary.

If this robotic arm is ever to be used by the common man, one of the most important considerations is the safety. When using powerful motors, metallic components, electronic circuits, etc. safety goes beyond just making sure there are no extruding sharp edges. A main power switch is a must. A switch must also be included which shall mechanically free the grip if pressed. The myoelectric electrodes must never output a voltage, since the skin might be very sensitive; thus a good grounding of the hand is required. Other safety features should also be incorporated later, without which no user will be convinced to use the hand.

These are some of the features which can be added onto the hand, though none of them are necessary. The foremost objective of the hand was to provide a usable and easy to use gripping prosthetic hand, which is possible without these features also, as designed.

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Other Sources

- Farnell Electronic Components Catalogue
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- Analog Devices Catalogue
- various Microchip publications on the PIC series

Appendices

Note: These appendices contain datasheets and commercial information intended only for research purposes. Reproduction any of the pages inside for use other than that intended for education or research is a punishable offence.

Microcontroller Datasheets
PIC16F87X, PIC12C67X, PIC12F675
In this section are a few relevant pages from the datasheets of the PIC series of microcontrollers decided to be used. These datasheets are readily available online on the Microchip website.

Pages 6

Motor Controller IC
BA6238A
Since we shall be using dc motors, a very reliable motor controller IC is being sold by ROHM. The technical information of this motor controller IC is given in this section. This has been downloaded from the ROHM website.

Pages 3

Myoelectric Electrode
MA 311
Technical information of the myoelectric electrode to be used in EMG analysis is given here. This electrode is commercially available with the Motion Lab Systems Inc. The details are available online.

Pages 2

Miniature Switch
ZP Series
For use in limit and bump switches, details are given here of a normally open sub-miniature switch which can be placed in the finger joints or on the actuation unit without wasting much space or weight. The details of this switch were also available online for download.

Pages 3

Force Sensor
FSL05N2C
The technical description of a piezoelectric force sensor is given here. This sensor includes the necessary circuit inside the small unit itself, saving space and weight. This sensor is manufactured by Honeywell and distributed by Farnell Electronic Components.

Pages 5

Note:
The online PDF version of this report does not contain the following pages of the appendices. To refer to the relevant information, kindly search for the component technical information online.

Thank You

Sameer Singh
Final Year
Electronics & Communications Engg.
Netaji Subhas Institute of Technology
New Delhi

August, 2003

As part of the Summer Training (2003) in Central Electronic Engineering Research Institute (CEERI), New Delhi, under the guidance of Mr. Amrik Singh, Robotics Division.