A CONCEPT MODEL FOR A MULTI-FINGERED PROSTHETIC HAND

BY

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DECLARATION

This is to certify that the design, calculations, tests and other work presented in this thesis are essentially my own and that no part of the thesis has been submitted for a degree at this or any other university.

Signed by candidate

J. Kotze
February 1997

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SYNOPSIS

The human body is undoubtedly the worlds most complex and functional mechanism of which much is, and probably will stay a mystery. From an engineering point of view the hand is probably the most fascinating part of the body. The hand is extremely versatile and loss of any part of it results in severe functional loss to the amputee thus leading to the desperate need to find a suitable substitute.

The various attempts by individuals to replace the hand has led to some ingenious and practical designs, but if compared to the real hand these designs are still light years behind. Till recently the most functional prostheses developed were body powered because of the simple, light weight designs. The designs for these hands have not changed must in the last few decades indicating that the design has reached its functional limit. This and the latest technology have initiated designers' renewed interest in externally powered prostheses. Existing externally powered hands only have one degree of freedom which limits the function of hands considerably whereas practical multi-fingered hands would provide a new dimension to the functionality of prosthetic hands.

For this project a concept model for a multi-fingered prosthetic hand was developed using Lego as design medium. The objective was to develop and test mechanisms as well as control strategies which can be used in a real prosthetic hand. A proper study of the human hand was done to determine its basic anatomy as well as its functioning. An extensive literature study on prosthetic and robotic hands was also done to evaluate existing designs and determine the level of existing technology. Special emphasis was laid on the anatomical design of the human hand which led to a model with a unique design. The model incorporates a tendon driven finger mechanism instead of the traditional linkage systems. This design provides an adaptable closing finger trajectory providing better grip. The model also provide actuation to all five fingers contrary to the three fingers of existing hands. This is achieved by a simple differential mechanism driving the last three fingers semi-independently with one actuator. The model also provides abduction of all fingers as well as opposition of the thumb improving the hands versatility. The hand is controlled using a personal computer and two interface boxes. Software was developed in Visual Basic to provide the user with a control analogue to that of a real myoelectric prosthesis.

The hand was tested and found to have real potential for further development. The mechanisms used are simple and practical and the controlling software can be replaced with programmable circuits. The tolerances on the all the mechanisms are very low leading to current instabilities but can be rectified by using more advanced materials and manufacturing techniques.

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GLOSSARY

Abduction: The angular deviation away from the medial axis.

Action potential: The electrical potential induced by the nerves.

Adduction: The angular deviation towards the medial axis.

Anatomy: The actual arrangement and construction of members.

Anthropomorphic: A device which is an imitation of a human counterpart.

ATP(Adenosine Triphosphate): A form of energy released to be utilised by the human body.

Body powered: Actuation is provided by parts of the human body.

Carpals: The eight bones forming the proximal part of the palm.

Central nervous system (CNS): The control system consisting of the brain and the spine.

Cineplasty: Tendons of muscles are connected through the skin control prostheses.

Cosmetic: Objects having a human appearance.

Cutaneous: Systems related to the human skin.

Dermal: The layer of the skin underneath the epidermis.

Dextrous: A device which is an imitation of a human counterpart.

Disarticulation: Removing one side of a joint during amputation.

Distal: The furthest point from the reverence point.

Endoskeletal: An internal skeleton.

Epidermal: The outer layer of the skin.

Exoskeletal: An external skeleton.

Extension: An decrease in the angular deflexion towards the reference zero angle.

Externally powered: Actuation is provided by any form other than the human body.

Extrinsic muscles: Muscles of which the bulk is located away from the point of actuation.

Flexion: An increase in the angular deflexion from the reference zero angle.

Hall effect: The phenomenon of electrical currents to produce a magnetic field.

Intrinsic muscles: Muscles of which the bulk is located close to the point of actuation.

Metacarpals: The bones in the palm of the hand connecting the carpals and the phalanges.

Opposition: The ability of the thumb to touch all the opposing fingers.

Phalanges: The three distal bones in a normal finger.

Pronation: Rotation of the forearm towards the outside of the body.

Proprioception: The ability to, without vision, detect the positioning of the parts of the body.

Proximal: The closest point to the reverence point.

Supination: Rotation of the forearm towards the inside of the body.

Tactile: The ability to detect touch.

INTRODUCTION

Chapter 1

The human body consists of a complex combination of systems and mechanisms all needed to perform the various intricate functions performed in every day life. Most of these functions are often taken for granted or totally ignored, yet they are very complex and mostly fully understood by man. If any of the parts of this system is not functional the effect on the rest of the body can be severe and the need to replace the system becomes crucial. The urgency to replace the body parts depend highly on the functionality of the part in every day life and its importance for the rest of the body to survive. This is partly why the development of artificial limbs are not as advanced as other more critical medical technology. Although very uncomfortable and hampering, the human body can survive without its limbs which effectively do not make them an absolute necessity. Further more the need for artificial arms are not as advanced as artificial legs, since walking is a far more essential function than the functions performed by the arms. Another great contributing factor is the fact that the functions and control of the arm is much more complex than that of the legs and thus more difficult to replace. Commercially available prosthetic arms are currently very simple and not very effective or cosmetic. Although prostheses designs are very ingenious the example set by the extremely functional human hand are so high that it can not really be compared to each other.

The development of functional prosthetic hands have also been hampered by the lack in specific technology which is sophisticated enough to compete with the high standard set by the human hand. The latest development in technology involving circuitry, actuators, power supply and materials have sparked new interest in the development of more functional hands. There is therefore much room for improvement in the design of the ultimate replacement for the human hand and hopefully enough technology available to achieve this which led to the initiation of this project.

The objective of the project is to develop a concept model for a more functional prosthetic hand. The development of a real prosthetic hand is a more long term and very expensive project therefore a concept model has to be developed first to evaluate and test the various mechanisms and control strategies on less expensive and available design medium. The medium decided on due to the availability was Lego. Lego is a very useful tool to use in concept designs developing useful principles. It presents the designer with real working mechanisms which can easily be constructed and evaluated and if necessary, be dismantled and changed. Lego has been used by the University of Cape Town as a design tool and for educational purposes for a few years and has proven to be very successful. Models developed by students are used in school programmes to spark children's interest in science and engineering. The prosthetic hand developed by the author has a dual function. It should present the principles to be used for further development of a real prosthetic hand and should also serve as an educational tool for children.

For the project a thorough study of available prostheses and technology is made to determine the need of amputees and the shortcoming of existing systems. This is needed to determine the focus of the project because prosthetics covers a very wide scope. A background study of the upper limb and the control systems of the human body is essential. To be able to replace something a thorough understanding of what has to be replaced and how is functions is an absolute necessity. Using this literature survey provides the background needed to develop a functional system. Together with a methodical evaluation of inventive concepts the optimal design for a prosthetic hand is constructed.

The aim of the project is not to build a hand with a performance equal to that of a real prosthetic hand but to develop concepts that could be used in the building of a real prosthetic hand. The performance of a prosthetic hand rely highly on the power delivered by the actuators and the tolerances achieved by the mechanisms as well as the effectiveness of the control system. It would be unrealistic to expect a hand designed and built out of Lego to perform in the same category as a real prosthesis because of the lower power outset and tolerances achieved by the components. Contrary to the performance of a prosthetic hand its functionality depends greatly on the basic design of the mechanisms. Since one of most important constraints put on the hand is the size of the hand together with high functionality the focus of the project was on the design of the most effective mechanisms to fit into the confined space of the hand.

The control of the hand is done through computer software on personal computer and is developed to be used by various age groups. The software simulates the controls provided by the amputee to a prosthesis. Using the hand as a educational tool requires the computer software to be adaptable to the needs of children.

THE HUMAN HAND

Chapter 2

Since the prosthetic hand's main function is to replace the human hand it is of absolute importance to make an in depth study of the human hand. To replace something it is vital to know what must be replaced. The human hand is an already designed, and perfectly working, device providing the best manual for the development of a proper substitute.

2.1 Basic structure of the hand

The hand consists out of five fingers of which four are essentially the same and a fifth which differs in design and function. To be consistent the fingers are numbered from the thumb being the first finger to the little finger being the last or fifth finger as illustrated in Figure 2-1. The fingers are named from first to last as: thumb, index finger, middle finger, ring finger and little finger.

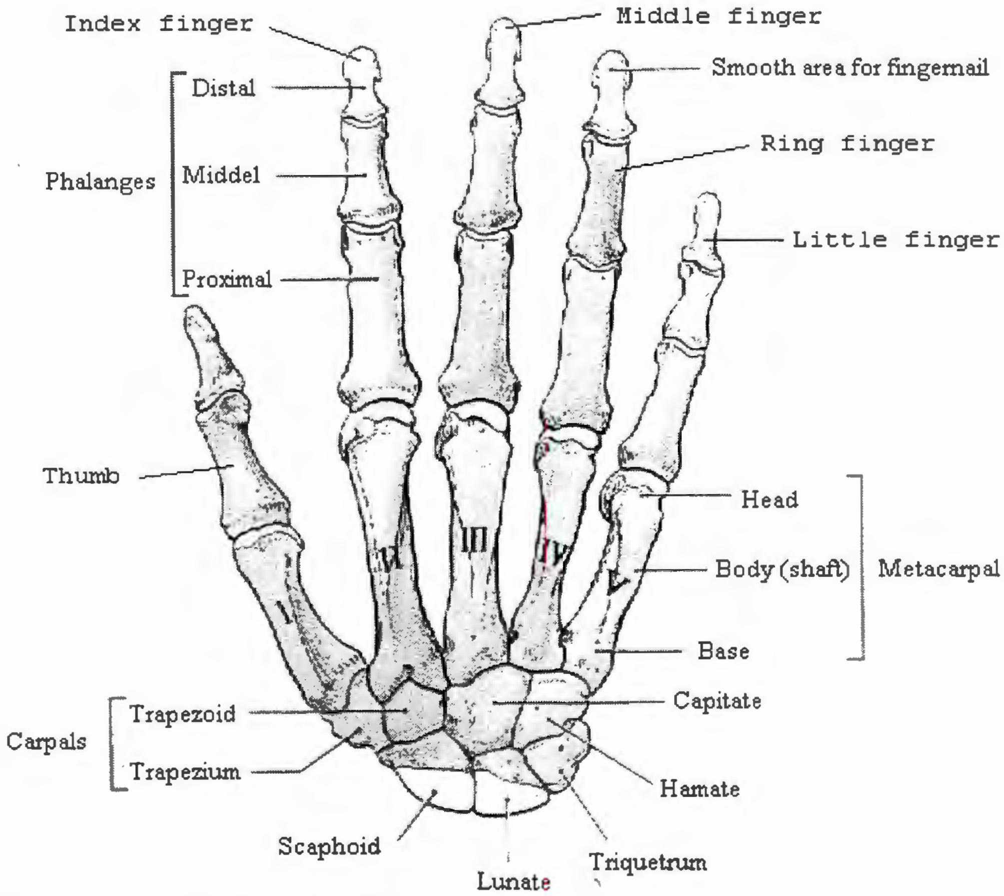


Figure 2-1: Anatomical view of the human hand

The human hand consists of 27 bones as shown in Figure 2-1 forming the palm and five fingers. The palm has 8 carpal bones and a metacarpal bone for each finger. Additionally each finger has 3 phalangeal bones (proximal, middle, distal), except the thumb which has two phalangeal bones(proximal, distal). The bones are connected to each other by joints and are stabilised by the surrounding ligaments and muscles.

The joints between the carpals and metacarpals are called carpometacarpal(CM) joints, between metacarpals and the proximal phalanges, metacarpophalangeal(MP) joints and the joint between phalanges, interphalangeal(IP) joints. The CM joints effectively allows no movement except that of the thumb and has two degrees of freedom giving the thumb the ability to oppose the other fingers. The MP joints of all the fingers allows two degrees of freedom while all the IP joints only have one degree of freedom. The movements achieved by the hand and the joints allowing these movements can be classified as:

- *Flexion/Extension* - MP and IP joints
- *Abduction/Adduction* - MP joints
- *Opposition* - CM joint of thumb

2.2 Muscles of the hand

The joints of the hand are powered by contractions of muscles attached to the bones. At the origin of the muscle it is connected directly to the bone while at the other end the muscle inserts onto the bone by means of one or more tendons. Tendons have a unidirectional fibre structure giving it very high breaking strength while the direction in which the force should be applied can be determined by various types of guiding mechanisms. Muscles and tendons can only apply or transmit tensile forces. Muscles are divided into intrinsic muscles situated in the hand itself and extrinsic muscles situated in the forearm. The major functions of the hand are performed by the *extrinsic muscles* (Figure 2-2 and Figure 2-3). The origin of the muscles are attached to the bones in the forearm. From the origin the muscles run longitudinally down the arm ending in tendons attaching to bones in the hand. The *intrinsic muscles* (Figure 2-4 and Figure 2-5) connect different bones inside the hand.

The function of muscles depend highly on the point of attachment on the bone and the line of action just at the attachment. The tendons of the muscles are guided by bone prominence, sheaths and retinaculi to enable the muscle to apply the forces in the right directions. The maximum force that the muscle can apply are relative to the size of the muscle. Some muscles perform more than one function because of the point of attachment with some having more than one point of attachment. It is only through the perfect co-ordination of all the muscles, controlled by the CNS(central nervous system), that the hand is so versatile and highly functional. Muscles normally control each degree of freedom of joints in antagonistic pairs. These pairs might be individual muscles or groups of muscles sharing the same function. The extrinsic muscles are divided into flexor and extensor muscles. The flexors are predominantly situated on the anterior side of the forearm and are responsible for closing the hand while the extensors are situated on the posterior side and responsible for opening the hand. Table 2-1 summarises the major functions of the muscles in the hand and forearm.[7,11]

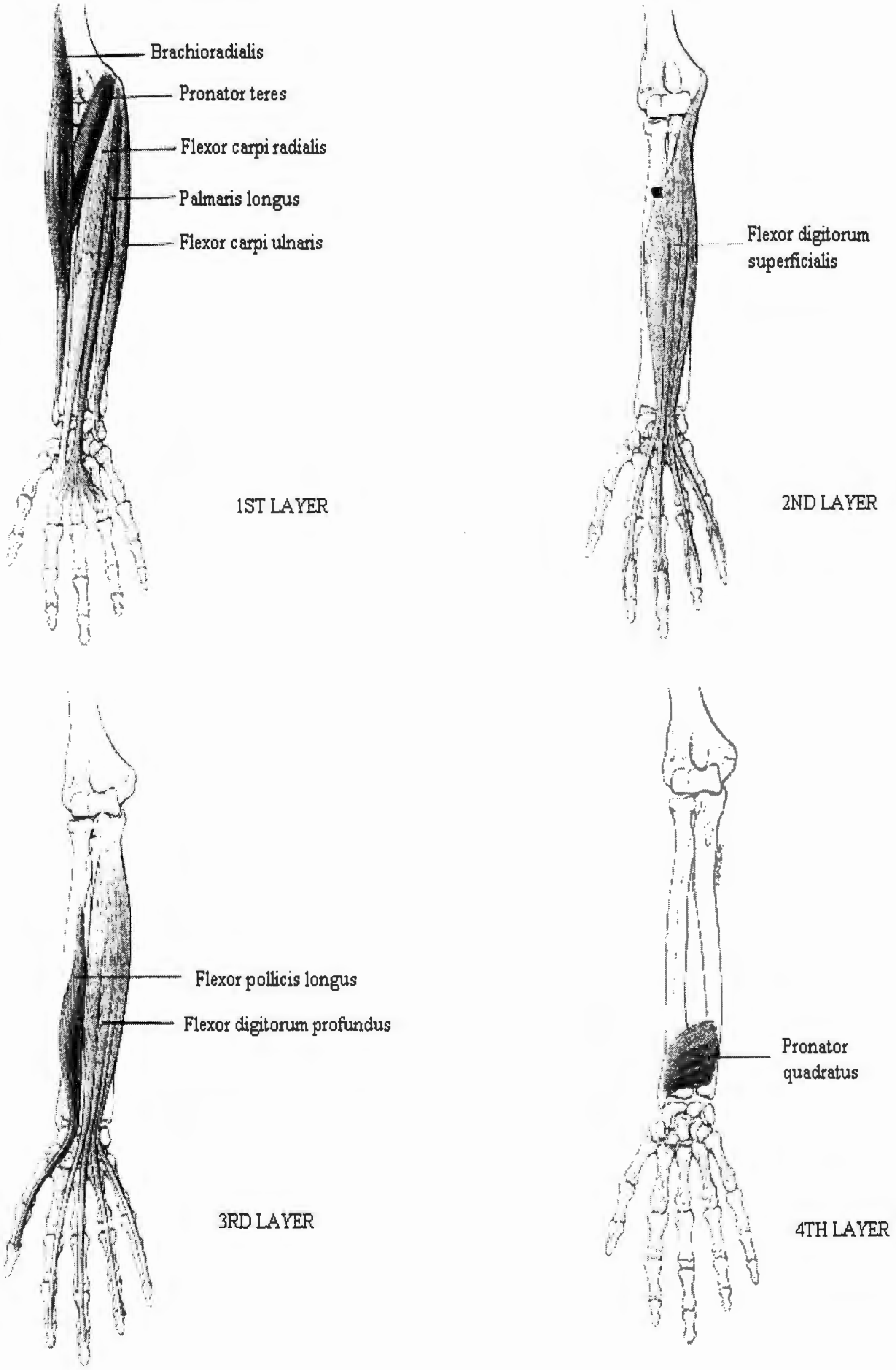


Figure 2-2: Extrinsic muscles of the arm (dorsal).

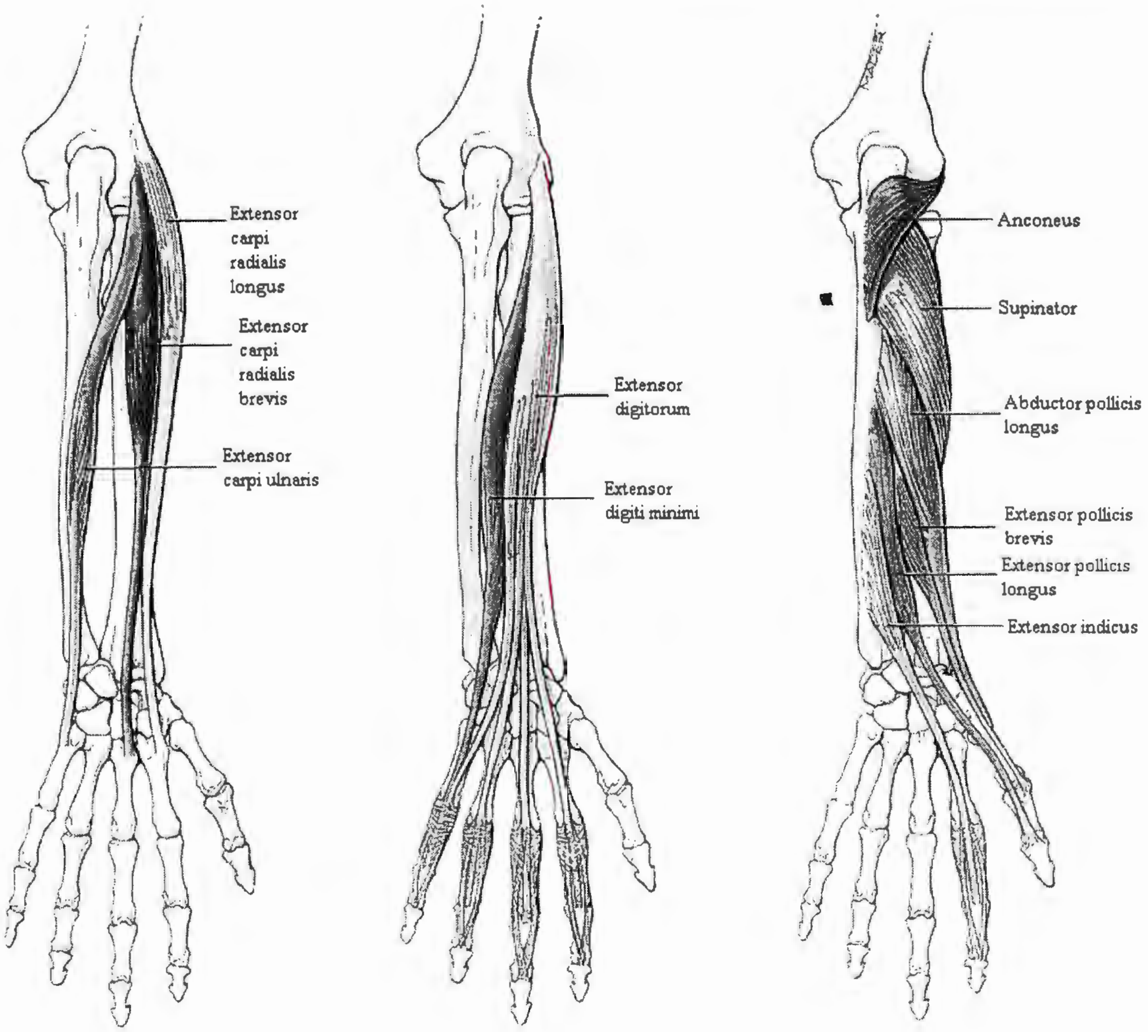


Figure 2-3: Extrinsic muscles of the arm (ventral).

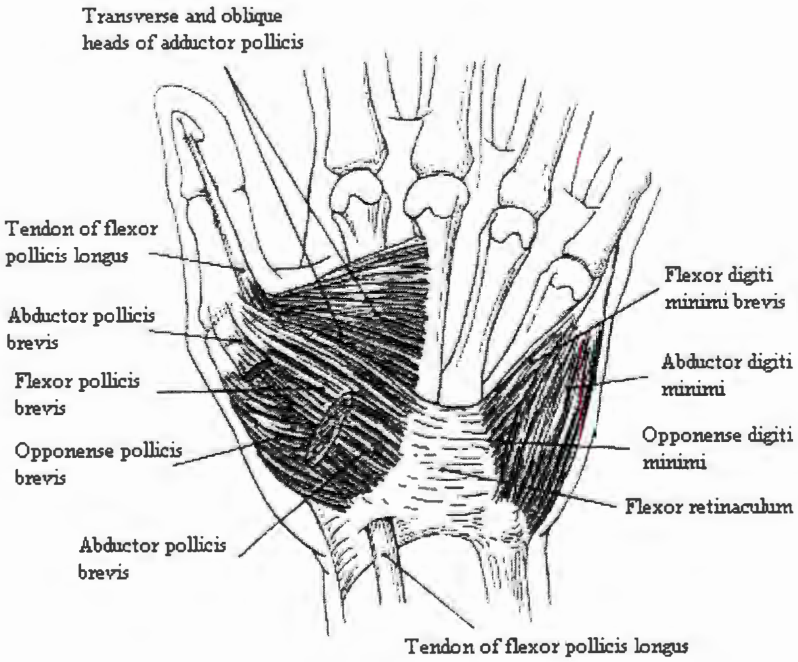
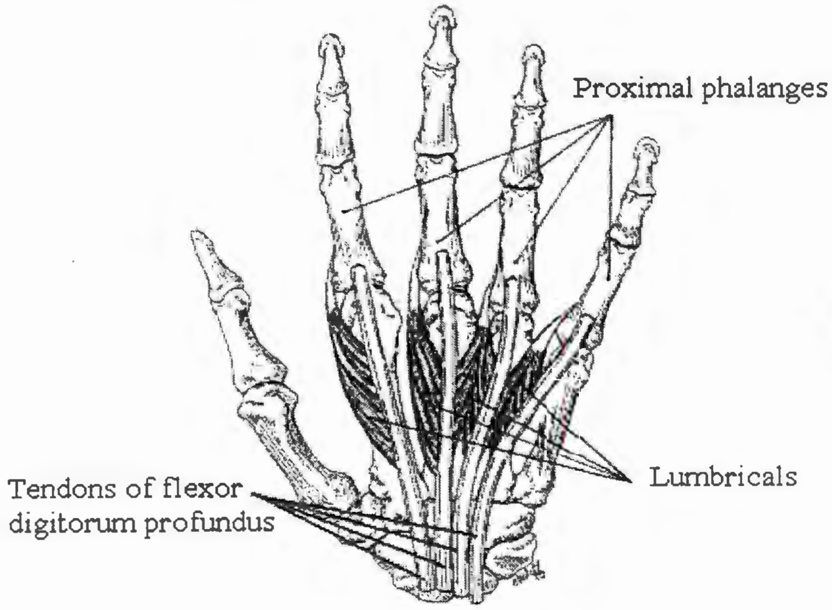


Figure 2-4: Opposing intrinsic muscles of the human hand.



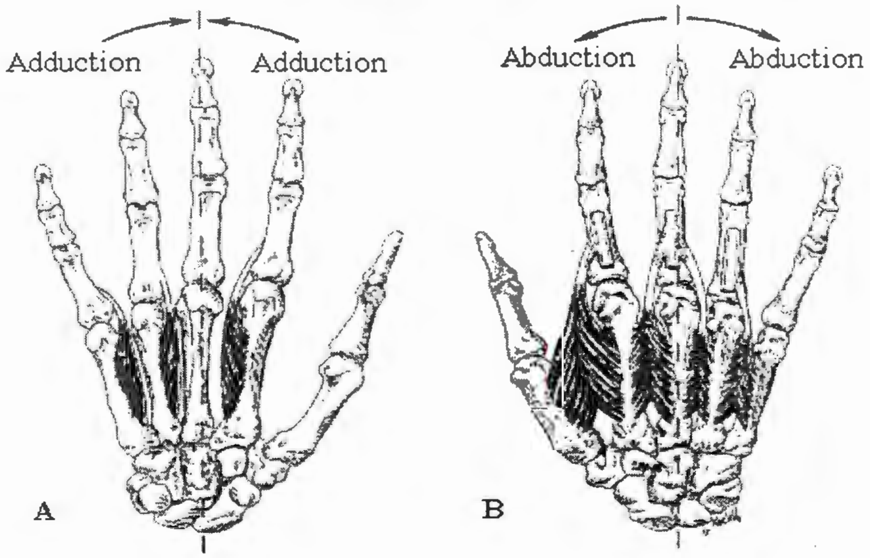
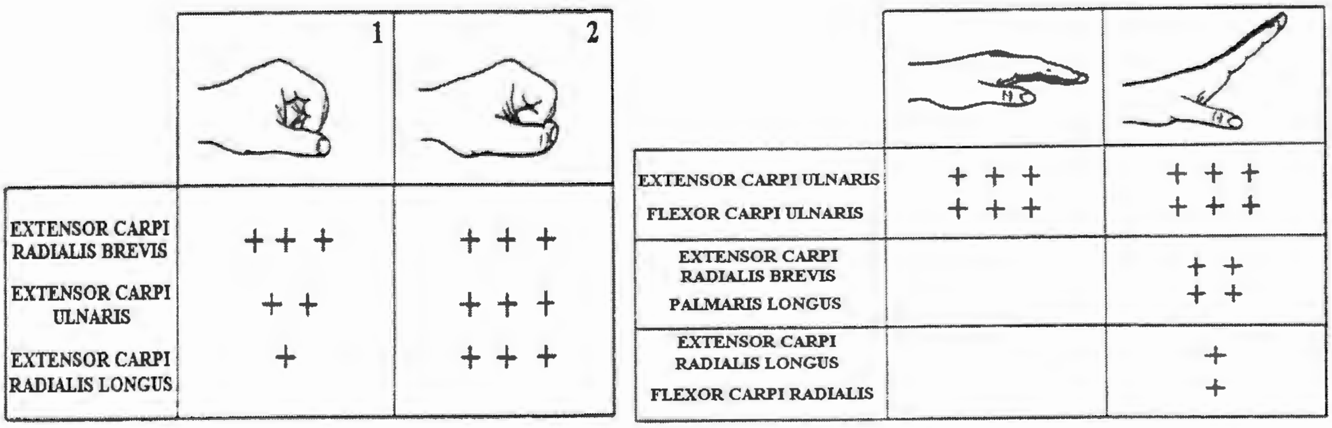


Figure 2-5: Abduction/adduction intrinsic muscles of the human hand.

Figure 2-6 shows the contribution of the major muscles of the hand during opening and closing of the hand.



	1	2
EXTENSOR CARPI RADIALIS BREVIS	+ + +	+ + +
EXTENSOR CARPI ULNARIS	+ +	+ + +
EXTENSOR CARPI RADIALIS LONGUS	+	+ + +

EXTENSOR CARPI ULNARIS	+ + +	+ + +
FLEXOR CARPI ULNARIS	+ + +	+ + +
EXTENSOR CARPI RADIALIS BREVIS		+ +
PALMARIS LONGUS		+ +
EXTENSOR CARPI RADIALIS LONGUS		+
FLEXOR CARPI RADIALIS		+

Figure 2-6: The contribution of the muscles during grasping.

MUSCLES	*FUNCTIONS*
Extrinsic muscles	
Palmaris Longus	flex wrist
Flexor carpi radialis	flex wrist, medially deviates wrist
Flexor carpi ulnaris	flex wrist, laterally deviates wrist
Pronator teres	pronate forearm
Flexor digitorum superficialis	flex wrist, flex 4 fingers
Flexor digitorum profundus	flex wrist, flex 4 fingers
Flexor pollicis longus	flex thumb
Pronator quadratus	pronate forearm
Extensor carpi radialis longus	extend wrist, medially deviates wrist
Extensor carpi radialis brevis	extend wrist, medially deviates wrist
Extensor carpi ulnaris	extend wrist, laterally deviates wrist
Extensor digitorum	extend 4 fingers
Extensor digiti mini	extend little finger
Extensor indicus	extend index finger
Extensor pollicis longus	extend thumb
Extensor pollicis brevis	extend thumb
Abductor pollicis longus	abduct thumb
Intrinsic muscles	
Thenar	flex, abduct thumb
Hypothenar	flex, abduct little finger
Opponense pollicis	oppose thumb
Opponense digiti mini	oppose little finger
Adductor pollicis	adduct thumb
Lumbrical	flex MP joints, extend IP joints
Palmar interosseous	adduct fingers
Dorsal interosseous	abduct fingers

Table 2-1: Muscles of the hand and forearm and their functions.

2.3 Special mechanisms in the hand

Most of the actions of the muscles are quite straight forward but there are a few very ingenious configurations that will intrigue most engineers. These mechanisms provide the optimum force application to ensure minimum power expenditure by the muscles of the hand. This contributes to the high functionality of the hand.

One such mechanism is the interaction between the tendons of flexor digitorum profundus and flexor digitorum superficialis (Figure 2-7). In the proximal parts of the hand the tendon of profundus runs deep to that of superficialis. The superficialis tendon attaches to the base of the middle phalanx, flexing the proximal IP joint, while the profundus tendon attaches more distally to the base of the distal phalanx, flexing the distal IP joint. To achieve this the tendon of the profundus muscle penetrates that of the superficialis muscle at the level of the proximal IP joint.

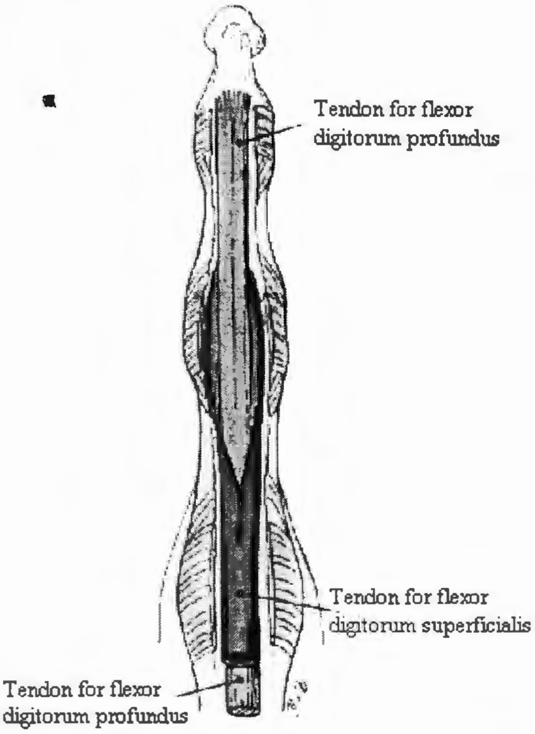


Figure 2-7: The superficialis and profundus tendon.

Another interesting mechanism is the extensor expansor as

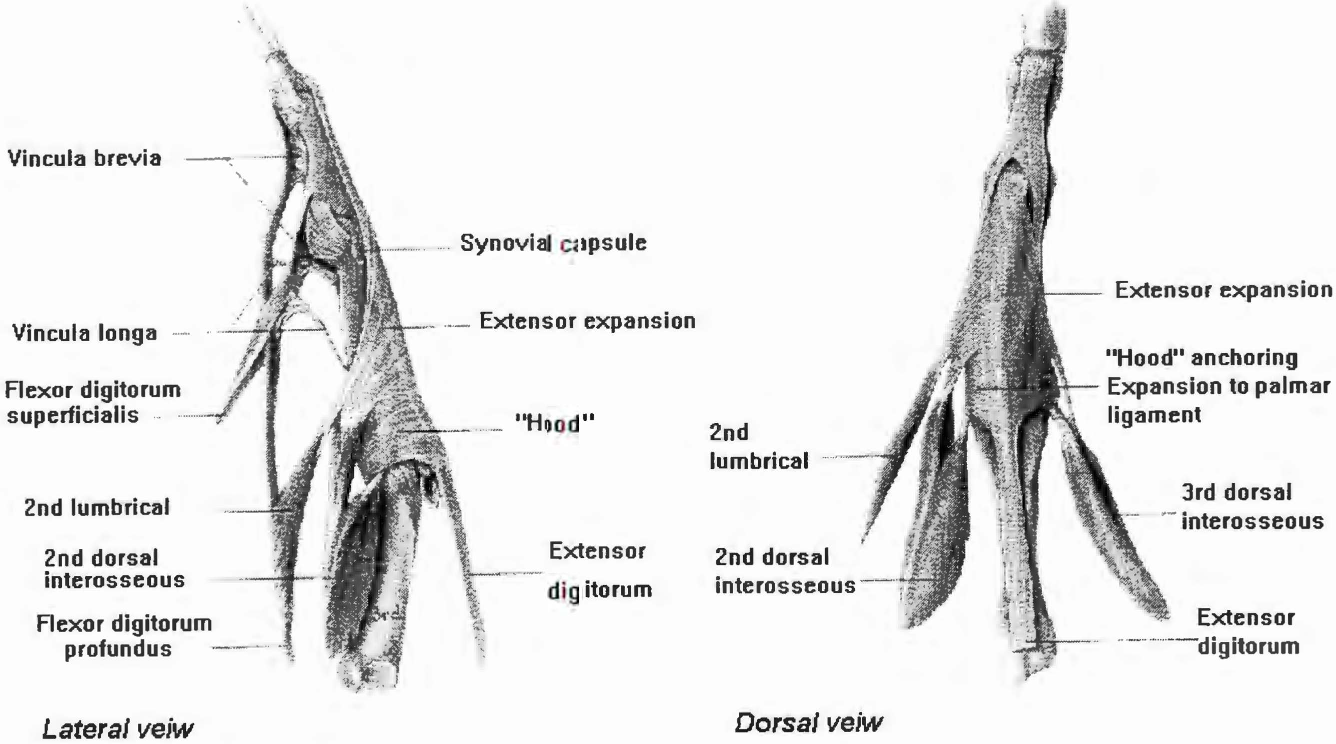


Figure 2-8: The extensor expansor mechanism of the finger.

shown in Figure 2-9. It is a complex configuration of tendons and ligaments in the finger, all merging from different muscles and applying forces at different parts of the finger. The tendon coming from the extensor digitorum muscle insert on the dorsal side of the expansor and extends the whole finger. The interosseous muscle on the other hand inserts from the dorsal side of the hand with one tendon inserting into the base of the proximal phalanx and the other into the expansor. The first mentioned abduct and adduct the fingers while the latter, due to its line of action, flex the MP joint and extends the IP joint of the finger.[7,11]

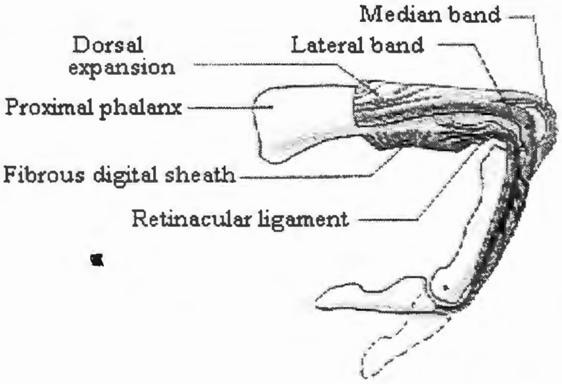


Figure 2-9: The functioning of the extensor expansor.

A close linked ligament to the expansor is the retinacular ligament shown in Figure 2-9. This fibrous band runs from the proximal phalanx obliquely along the side of the middle phalanx and the two IP joints to join the expansor on the dorsal side. On flexing the distal IP the ligament tighten, flexing the proximal IP joint. Similarly flexion of the proximal IP joint leads flexion of the distal IP joint. Simultaneously there is another mechanism (Figure 2-10) aiding the flexion of the finger by relieving undue resistance. The expansor attach distally through the medial band into the base of the middle phalanx and through the lateral band into the base of the distal phalanx. Flexing the distal joint pulls the lateral band and the trifurcation forward, relaxing the middle band assisting in the flexing of the proximal IP joint. At the stage, during further flexion, when this joint angle is larger than 70 degrees the middle band tightens relaxing the lateral band, making flexing of the distal IP joint easier.[3]

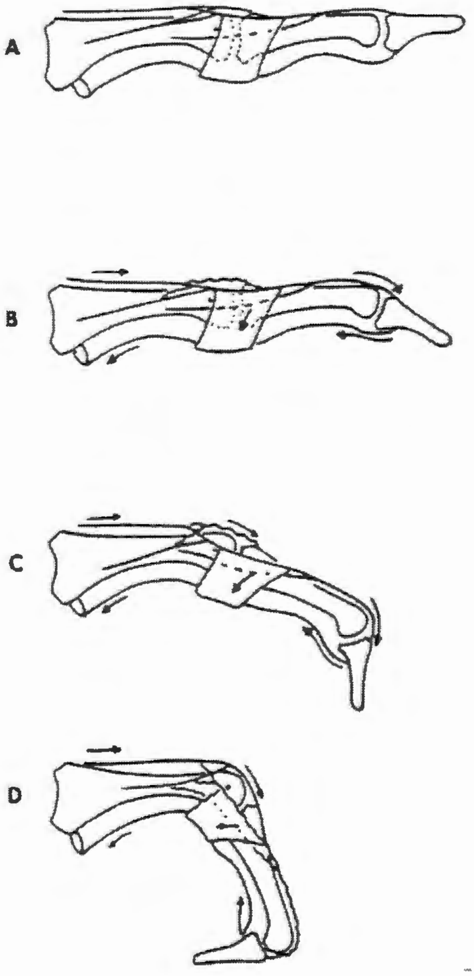


Figure 2-10: Additional flexion mechanism for the finger.

Some of the fingers have additional or separate extrinsic muscles for better independent control. The index finger and little finger each has one additional extensor muscle. The thumb is unique from the other fingers and has two separate extensor as well as a separate abductor and flexor muscle. The additional muscles to the thumb provides additional and wider range of motion to the thumb as shown in Figure 2-11.[11]

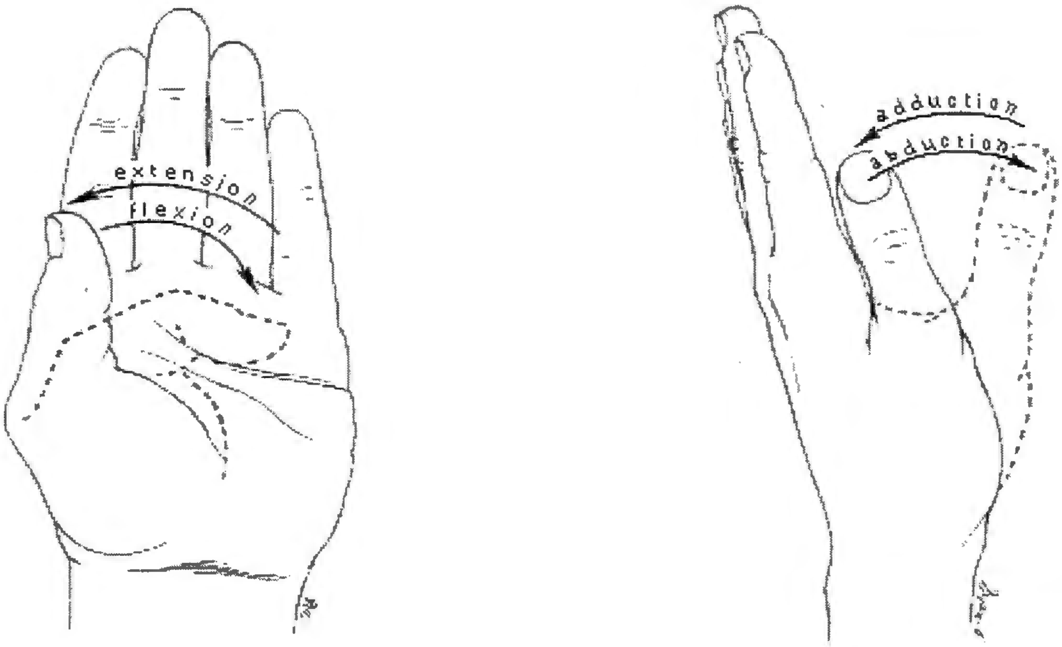


Figure 2-11: The range of motion of the thumb.

The range of motions of the finger joints in the average human hand are given by Table 2-2. The motions of the thumb joints are unique while that of the remaining four fingers are similar.[15]

FINGER JOINTS	*RANGE OF MOTION*
Thumb(1)	
CMC joint	15°
MP joint	0-50°
IP joint	0-80°
Normal fingers(2-5)	
MP joint	0-90°
Proximal IP joint	0-110°
Distal IP joint	0-65°

Table 2-2: The range of motion of the finger joints.

2.4 The functions of the hand

The most important functional activities of the hand can be divided into different categories:

NON-PREHENSILE: touching, feeling and related functions

PREHENSILE: gripping and manipulation objects

- *Precision:* A week grip on the radial side of the hand between the thumb, index and middle finger forming a three-jaw chuck(index grips).
- *Power:* A strong grip on the ulnar side of the hand between the thumb and all the other fingers(hook, spherical, cylindrical grips).[29]

It should be very clear that the human hand is an extremely versatile and complicated gripping device. There will probably never be a substitute matching the versatility of the hand but any progress in that direction can be of major assistance to the amputee. There is thus incredible room for improvement in prostheses and more than enough motivation to pursue this development.

LITERATURE REVIEW ON PROSTHESES

Chapter 3

3.1 History

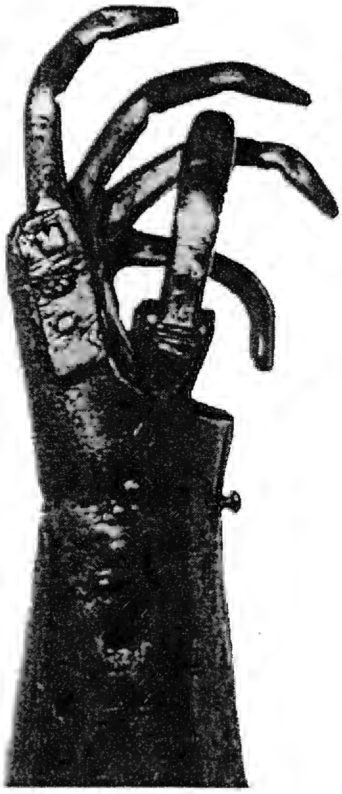


Figure 3-1: An Iron hand dating from 218-202 BC.

The earliest record of an upper limb prosthesis is the iron hand of the Roman General, *Marcus Sergius*, who lost his right hand in the 218-202 BC and was fitted with a iron hand. In later years iron hands were developed with the user being able to set the fingers in a flexed position, as shown Figure 3-1. The purpose of the hand was to hide the users deformity and restore some function. The number of amputations increased considerably during the 14th century due to disease, warfare and the introduction of gunpowder in battle. Fabricators of prosthesis in these times were mainly the makers of armour and shields which provided war amputees with devices to assist them in battle. The ordinary man were seldom fitted with prosthesis, and when fitted, the device only provided cosmesis. A simple hook replacing the forearm was used for quite a while. It was quite useful but not aesthetic at all. The hand shown in Figure 3-2 is another iron hand dating back to about 1400. The hand has a fixed thumb, flexible fingers which can be closed passively and locked with a ratchet mechanism and a adjustable wrist. The best documented patient of the early years was the German Knight, *Götz von Berlichingen,* who invented a mechanical device to replace his own hand in 1509.

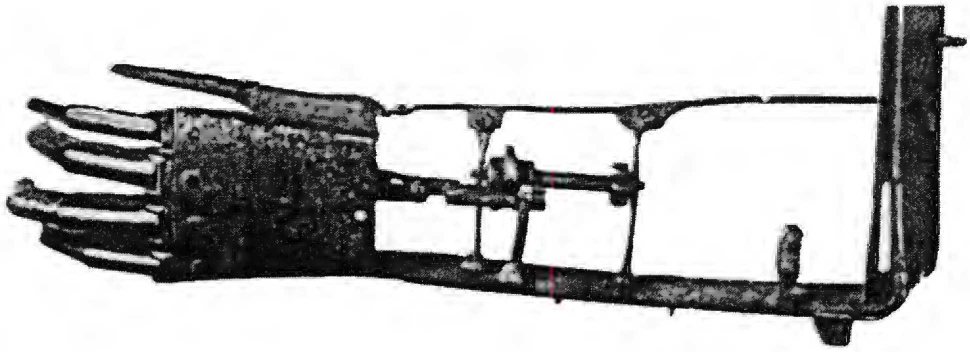


Figure 3-2: Iron hand dating from 1400 AC.

Figure 3-3: Wooden hand of John Carew made in 1601 AC.

There are no reports of articulated wooden hands before the nineteenth century except for that of *John Carew*, made in 1601. This hand, as shown in Figure 3-3, was carved out of wood with metal hinges and channels cut in the back for control cables. The thumb has a ratchet allowing it to be set into different positions. Up to this stage prostheses could still not be controlled voluntarily , they could only be set in certain positions. *Peter Baliff*, a Berlin dentist, developed the first system to utilise the shoulder girdle muscles as a form of power to flex or extend the fingers in 1818. This system was only used for below elbow amputations. Only in 1844 the Dutch sculptor, *Van Petersen*, used Baliff's principles to power the first above elbow prosthesis. The prosthesis allowed shoulder flexion/abduction, elbow flexion/extension and active finger extension.[20,25,26,31]

A Frenchman, *Comte de Beaufort,* developed a prosthesis in 1867 of which some of the principles are still used today; a hand that can open and close by repeatedly pulling on the same cord, passive elbow flexion and a double spring hook for gripping objects. It used a worm gear to flex/extend the metacarpophalangeal joints. In 1886, *Clasen* developed the first heavy-duty prosthesis capable of holding heavy objects. A few years later, in 1904, *Carnes* developed a prosthesis of which the fingers could flex, the wrist flexed/extended, pronated/supinated and the elbow flexed/extended. *Dorrance*, in 1912, developed the first split hook which is still in use in modern day prostheses. Later in 1919, *Borchard et al* invented a electromagnetically powered hand. The index and middle fingers were pushed against each other by switching on a circuit. This was never used due to the lack of a proper control system and energy storage devices.[20,25]

In the 1940's the Second World War led to quite an explosion in the development of prostheses and a lot of research programmes were initiated. According to reports, *Erlangen* developed a electrically powered hand in 1945 but the design was never documented. Later in 1949, another electrically powered hand, the *Vaduz* hand was developed. This hand integrated a drive with the already existing mechanically driven hand developed earlier by *Hüfner*. The difference in diameter between the contracted and released residual limb was used to control the hand. In the same year work was done by the American, *Alderson,* in developing an electrically powered device. The use of electrical energy only became significant for prostheses after the development of myoelectrical control. The pioneering work in myoelectrical control was also in progress at the same time span, by *Reinhold Reiter* in Munich. This hand used amplified electrical currents resulting from muscle contraction as trigger impulses for the control of its electromechanical components. It had a bulky control unit which was placed on a bench next to the user. This and the unfavourable post-war economic situation lead to no immediate interest in his work until later in 1959. Except for the development of externally powered systems not much has changed in upper limb prosthetic designs since the 1950's. The Russian, *Kobrinsky*, developed a system in 1961 that had a control unit twice the size of a cigarette box and was worn around the waist of the user together with the power pack. The prosthesis worked well but was unreliable, too big and had a high energy consuming circuitry. The first really efficient myoelectrically controlled prosthesis were developed by *H. Schmidtl* in 1965 in Italy. The successful use of myoelectric prosthesis requires an institutional setting with the backup and the support of medical and therapy staff. In 1960 work was done in Germany in the development of pneumatic systems but was halted due to a lack of funds.

The approach for developing prostheses was to develop a variety of components that could be assembled to meet the needs of the amputee, rather than to develop a special system for each level of amputation. The *APRL* hook was developed by the Army Prosthetic Research Laboratory as a voluntary closing device. It was developed in various sizes and is still in use today. The first commercially developed system outside Russia was that of *Zeman,* in Vienna in 1964. The system was combined with the *Otto Bock* hand, with the latter developing into a system of its own in 1967. *Scott et al.* developed a system to perform without electrode paste to replace the three-state system. *Smidtl* and *Scott et al.* developed systems with sensory feedback.[20,26,3]

3.2 Amputation principles

There are still different perceptions on the preferred site of limb amputation for the amputee. Some surgeons prefer to make the stump as long as possible, leaving as much as possible of the residual limb for attachment of the prosthesis and to maintain as much of the functionality of the limb. A good example of a critical amputation level is the choice between a wrist disarticulation and a more proximal amputation. The disarticulation leaves the user with additional length and surface area and the radio-ulnar joint for better pronation/supination of the wrist. Another consideration is additional sensory feedback provided by the residual limb.[14]

The opposing principle is to amputate the limb at such a level that it provides sufficient space to fit in the various prosthetic devices such as wrist units, connecting components and power and control devices. Amputees are usually reluctant to go through revision surgery to correct this. In Figure 3-4 the shaded areas showed the preferred positions for amputations and the dark lines indicate positions that should be avoided.[20] Due to the extremely functional nature of the hand itself in terms of gripping and sensory feedback the trend is to amputate as little of the hand as possible. The residual hand can either be surgically reconstructed into a very useful tool or be fitted with a partial hand to assist in the function of the hand.

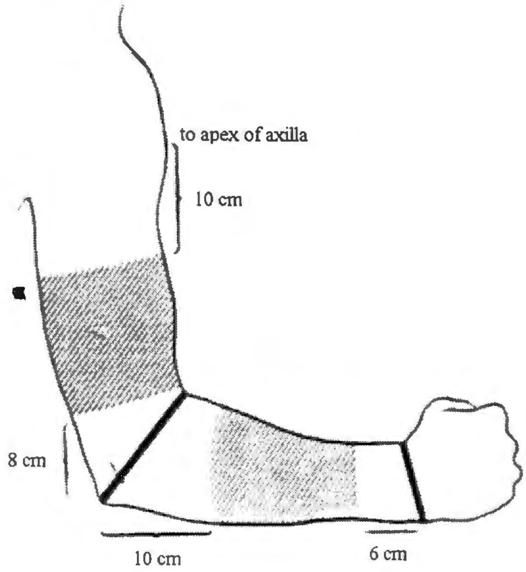


Figure 3-4 Preferred amputation sites of the upper limb.

3.3 Principles of prosthesis design

It is important to realise that currently, with all the available technology, designers are not even close to reproducing the human hand. Thus far the most elaborate artificial hand can only be a moderate substitute for the real hand. The human hand cannot be replaced by a prosthetic device, the device can only reproduce some of the lost functions of the hand. Though machines are able to outperform the human in various specific applications, no machine can address the variety of tasks performed by the hand. The best method of replacing the functions of the hand is to try to perform those tasks which make it such a versatile prehensor.[8,26] The most important properties of prostheses have been established as:

- functionality
- cosmetic appearance
- low cost
- light weight
- restricted shape and size
- low power consumption
- quiet operation
- robustness
- stability
- serviceability
- comfort
- interchangeable components [3,22,26]

The major challenge is to design prostheses satisfying all these requirements as best as possible. Currently there are certain trade-offs to be made because an improvement in some of these properties often leads to the loss in others.

The main purpose of the prosthesis is to replace the missing limb and to restore its function to the fullest extend, which includes sensory input, voluntary motor action and psychological loss. The importance of functionality as opposed to cosmetic appearance of the prosthesis varies between amputees. This depends on the personality of the individuals, work requirements and the degree of acceptance from their social surroundings. People with office jobs or those from a very appearance conscious society will be more concerned with the natural appearance, texture and colour of the prosthesis, with its motor function being a secondary requirement. Studies showed that for these users there is often an equally strong need for cosmetic appearance at the covered upper extremities of the arm as for the visible part of the hand. For people with more physical jobs or those who are part of societies which are less appearance conscious the function of the prosthesis is of primary importance. Often the prosthetic devices that are useful and functional do not resemble the human hand shape.[25,3]

The difference between prosthetic interface and normal man-machine interface is that the latter is controlled by the hands or the feet of an individual but in the case of prostheses other forms of control must be used because of the absence of the limbs being replaced. The acceptance or rejection of a prosthesis depends on the balance between the benefits to the user and the drawbacks of the system. Improving one aspect often leads to a decrease in the other. The basic design for prosthetic hands are very similar and all the connections between components are standard to ensure interchangeability between systems. The high standards set on the prostheses leads to equally high standards on the materials used. It is essential that these materials are strong, lightweight, bio-compatible, durable and malleable.[2,3]

Currently the rejection rate of prostheses by users is very high. To make the hand truly functional it needs to be very complex which leads to controlling difficulties and a heavier and more fragile prosthesis. This and the ability of the patient to function effectively with the residual limb and the remaining normal arm are the main reasons why many unilateral amputees reject prostheses. The rejection rate of prostheses by bilateral amputees is lower because the disability is so severe that any additional function is much needed.[3] With the current stage of development the only interface between the prosthesis and the body is the skin which presents a few drawbacks to further development. The use of sockets to attach the prostheses to the body will be used until a method is devised of achieving a permanent fixture between the body and prostheses. It is hoped that in future skeletal attachments and control devices penetrating the skin might be developed to eliminate most of these problems. The load carried by the prosthesis is translated to the arm through the socket, the skin and the muscles and is not translated directly to the bone as in the human body. The skin is not very tolerant to pressure for pain levels and vascularity and therefore the forces generated by the prosthesis must be spread over the widest possible area.

Terminal devices representing the human hand in appearance are called anthropomorphic or dextrous. The structure of prosthetic hands can be either exoskeletal or endoskeletal. An *exoskeletal* structure is hollow and the forces are transmitted through its hard shell while an *endoskeletal* structure has a central part transmitting the forces. The central shaft of the latter case is surrounded by a soft material providing a more natural feel to the structure. Cosmetic components of the prosthesis represent the soft tissues of the limb and provide shape or a protective skin to the prosthesis. The skin can be either enamel or matt-finished paints, coloured leather, glass or nylon fibre or similar material impregnated by plastic. The latest trend is to have an soft outer layer covering the inner components and frame which is covered with a cosmetic glove. This provides a life like appearance and a natural soft feel to the prosthesis. The gloves are sensitive to sunlight, difficult to wash and not resistible to various inks. Another important factor is the natural kinematic appearance during movement. Soft cosmetic forearms, made from plastic foam, surrounding the aluminium core is aesthetic, light weight, not noisy and can be adjusted to the skin colour. High-strength translucent latex is used to produce cosmetic gloves and resists oxidation and most stains.[3]

3.4 Developed terminal devices

3.4.1 Partial hands

Various body powered partial hands are available for partial hand amputees. The normal trend it to retain as much as possible of the original limb during amputation. This is mainly because of the additional sensory feedback supplied by the remaining limb and especially the skin. It is also amazing how useful any additional part of the body is compared to the replacing prosthetic equivalent. These hands are normally some variation of the normal body powered hook with unique attachments to the hand to fit the shape of the specific individual. Some devices differ from this though and employ different techniques using residual fingers opposing a strap-on device to supply sufficient grip. Devices either use the remaining fingers to provide the grip, or modifications of hooks powered by flexion/extension or radial/ulnar deviation of the wrist or flexion/extension of the elbow or shoulder. In all these cases it is of great importance that the contact area between the gripping device and the hand is a minimum, without sacrificing stability of the device. This ensures the optimal use of the remaining sensory feedback of the remaining limb.[14]

3.4.2 Hooks

The principles for the design of the hook have not changed much since the early 1900's. There are predominantly body powered but some externally powered designs exist. Hooks are not very aesthetic but are extremely functional and therefore popular with users not so concerned with cosmesis of the device. Advantages of hooks includes:

- functionality
- light weight
- versatility
- simplicity
- robustness
- durability
- high pinching forces
- object is very visible [3,14]

Most hooks uses body power and are predominantly voluntary closing but some voluntary opening models also exist. The reason for the preference to voluntary opening hook is the conservation of energy during use because the user does not have to contract the muscle to maintain a constant grip on the object. Pulling on a cable connected to the jaws opens the voluntary opening hand while elastic bands are fitted around the two jaws to provide the grip force. With the voluntary closing hand the tension on the cable has to be maintained to apply a continuous gripping force. The elastic bands can be replaced easily and adding more or stronger bands to the hook increases the gripping force of the device. Some manufacturers have developed cosmetic gloves to fit over hooks to make it more aesthetic.

The *APRL* hook developed by the Army Prosthetic Research Laboratory as a voluntary closing device which locks after gripping the object. The locking mechanism conserves the users energy because constant force on the object is applied without continuous muscle contraction. It was developed in the 1950's in various sizes and is still in use today with the basic concept still being the same. The United States Manufacturing Company (*USMC*) hook is voluntary opening and has a small triangular opening in the stationary finger for additional attachments. The voluntary closing terminal devices shown in Figure 3-5 were developed by *Bob Radocy*. The Michigan hook, shown in Figure 3-6 is a very simple device developed for children. *Hosmer/Dorrance* developed various models of voluntary opening hooks(Figure 3-7) including the unique lyre-shaped fingers to grasp round objects and neoprene or plastisol covered fingers for better grip. Another hook is the *Trauteman Locktite* hook shown in Figure 3-8. *VAPC* developed a electric hook(Figure 3-9) which is interchangeable with its powered hand counterpart.[3]

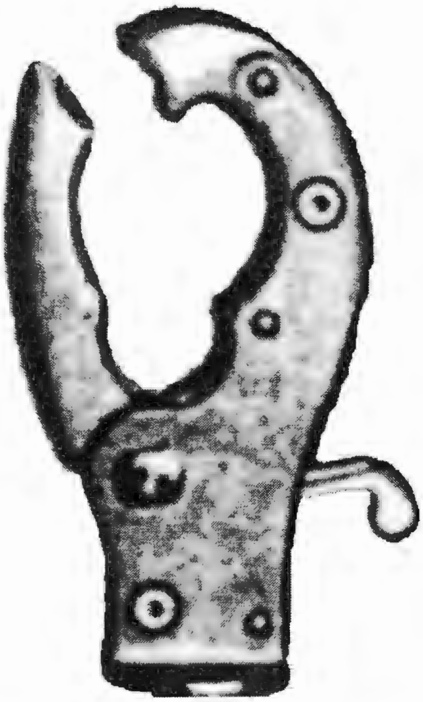


Figure 3-5: The voluntary-closing terminal devices of BobRadocy.

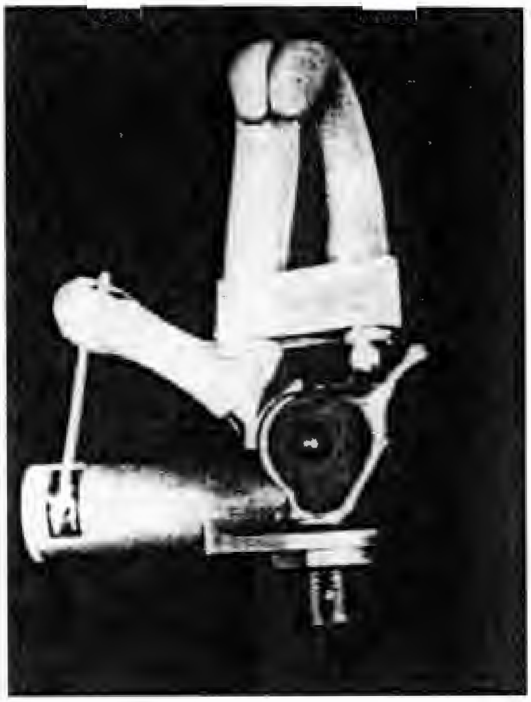


Figure 3-6: The electrically powered Michican hook.

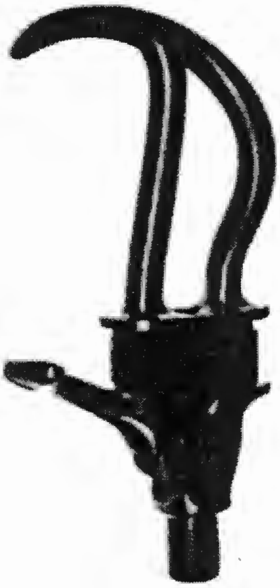


Figure 3-7: The Hosmer/Dorrance hook.

Figure 3-8: The Trauteman Locktite hook.

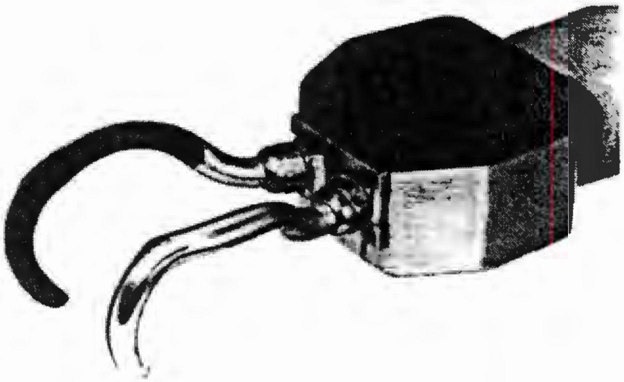


Figure 3-9: The VAPC electric hook.

3.4.3 Special gripping devices

The *CAPP* (Figure 3-10) terminal device is a unique voluntary opening hand with its gripping surface covered with contoured rubber material. The device supplies a superior grip to the child amputee. The *Greiffer*(Figure 3-11)gripping device is a non-anthropomorphic hand, developed by Otto Bock, which produces high gripping forces. The device can withstand more abuse than more fragile prosthetic hands and does not have a fragile cosmetic glove. It consists of multiple durable hard plastic shells with rubber padded or non-padded gripping surfaces. The distal prehension surfaces remain parallel during prehension. The device has the same automatic transmission system as the Otto Bock hand.[3]

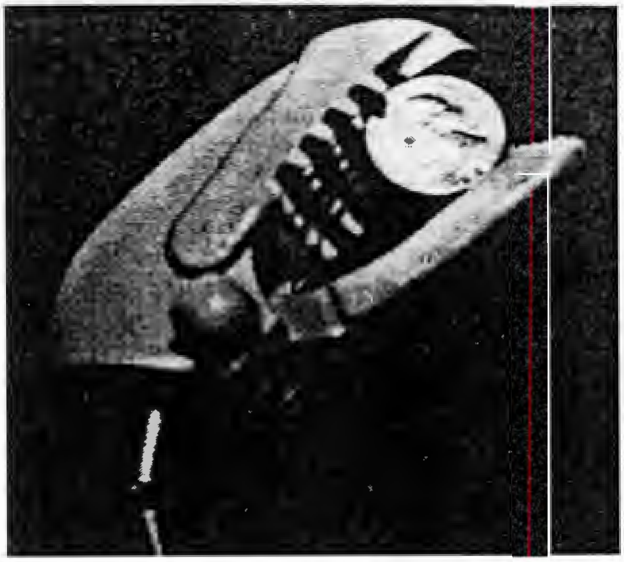


Figure 3-10: The CAPP voluntary opening terminal device.

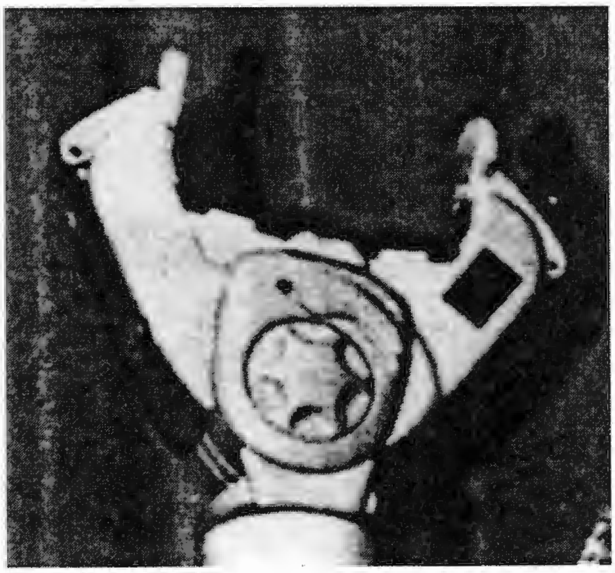


Figure 3-11: The Greiffer terminal device.

The *NASA Rotational hand* is unique in that it opens and closes with pronation/supination of the forearm. The hands advantages includes:

- inexpensive
- comfort
- durability
- light weight
- easy to use [27]

3.4.4 Prosthetic Hands

3.4.4.1 Commercial hands

Commercial hands are functional but often not aesthetic mainly because of the additional cost involved to make a cosmetic device. Designs are very simple, durable and easy to use. Currently various concepts are under investigation or being developed but are not truly functional and therefor commercially available.[23]

Body powered hands

Commercially available hands share the following characteristics:

- All hands and hooks have 1.3 to 50 cm length studs for attachments to the forearm socket.
- The basic pattern for finger motion is palmar prehension.
- The correct hand size for selection is determined by the circumference of the metacarpophalangeal joints of the non-amputated hand.
- Most hands are covered with a cosmetic glove.

Becker Plylite hand(Figure 3-12): It is a simple, light weight, voluntary opening hand with the thumb as the only moving component. The thumb can also be locked in a closed position.

Becker Lock-Grip and Imperial hand(Figure 3-13): The hand is voluntary opening with all five fingers opening and a mechanism that can lock the fingers in the closed position. The Imperial model provides additional adjustment of the prehension force using a screwdriver.

Robin-Aids hand(Figure 3-14): This is a voluntary opening hand with all the fingers moving away from the stationary thumb. The latter can be manually prepositioned and the prehension force adjusted by changing the springs. The hand is the only hand with an adjustable wrist length permitting it to be used by a wrist articulation as well as a long below-elbow amputee.

Figure 3-12: The Becker Plylite hand.

Figure 3-13: The Becker Lock-Grip and Imperial hand.

Figure 3-14: The Becker Lock-Grip and Imperial hand.

Figure 3-15: The Robin-Aids hand.

Soft Robin-Aids hand(Figure 3-15): The hand is voluntary opening, with the thumb and the first two fingers opening. The endoskeletal frame of the hand is encased in plastisol and covered with urathane foam.

APRL voluntary closing hand(Figure 3-16):Tension on the cable causes the first two fingers to move towards the stationary thumb. Relaxing the cable after the object is gripped will cause the device to lock. The re-application of tension unlocks the device again. The thumb can be manually prepositioned.

Sierra voluntary opening hand(Figure 3-17): The hand is essentially the same as the APRL version except for being a voluntary opening hand and having a locking mechanism to lock the fingers after gripping of the object has occurred.

Figure 3-16: The APRL voluntary closing hand.

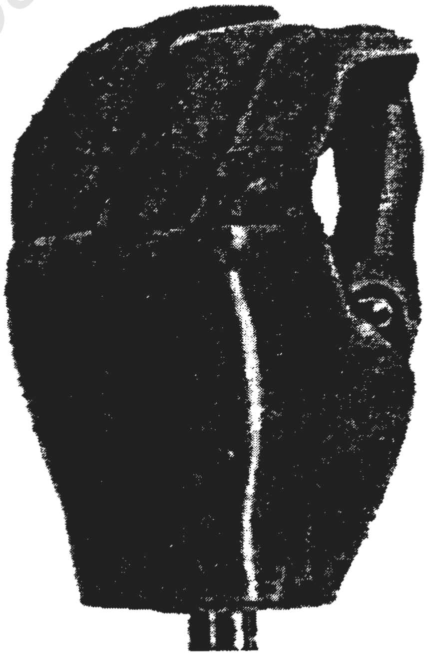


Figure 3-17: The Sierra voluntary opening hand.

Otto Bock hand(Figure 3-18): The hand consists of four basic components; a standard chassis and wrist plate, operating mechanism, inner hand and cosmetic glove. Various mechanisms accommodated by the chassis includes; cable-operated voluntary opening and closing, electrically and pneumatically powered and passively operable mechanisms.

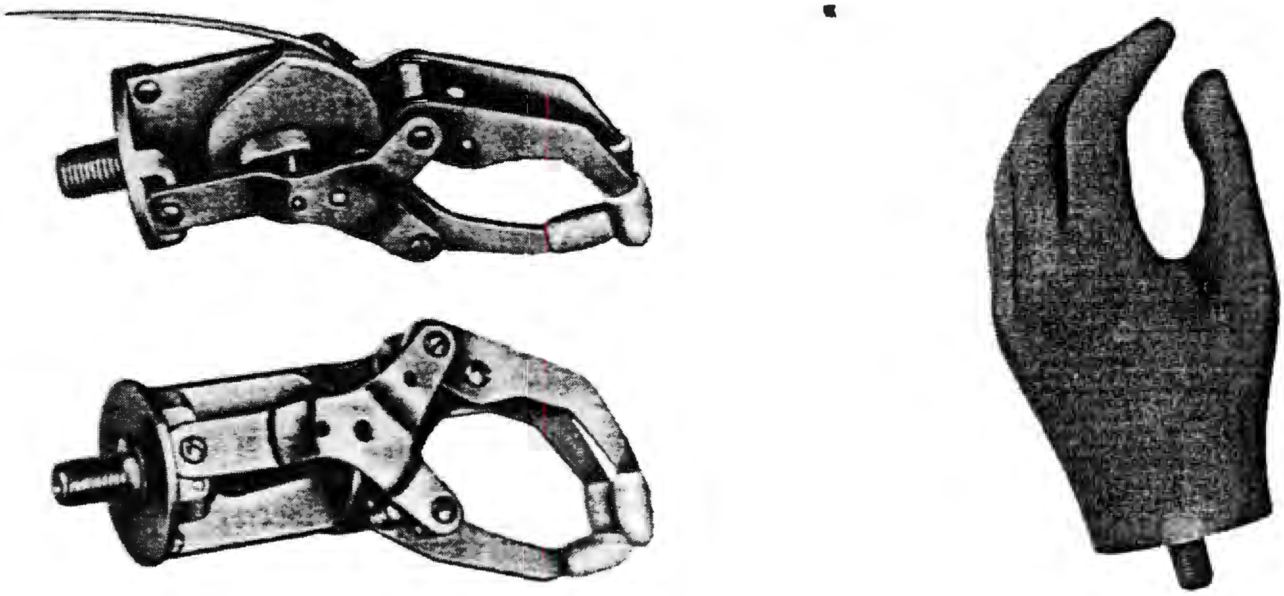


Figure 3-18: The Otto Bock voluntary opening or closing hand.

Non-functional cosmetic hand: The hand consists of a malleable wire frame imbedded in a flexible foam plastic and covered with a cosmetic glove.[3]

Externally powered

The basic concept for externally powered hands are the same as body powered hands. The cable which opens or closes the hand is replaced by another external energy source. The difference in design is thus mostly in the space and power considerations. In the body powered device the actuator was a different muscle group than was used to actuate the same motion in the real hand. The actuator of the body powered hand therefore does not fit into the hand itself as with externally powered hands. All the hands being described have dependant movement of individual fingers and all have fixed prehension patterns which means only one actuator is needed. One of the main advantages of body powered prosthesis is the improved cosmesis due to the lack of harnessing. Fitting the prosthesis with non-cosmetic gripping devices defeats this advantage and leads to the development of predominantly dextrous, externally powered prehensors.

These hands are normally fitted with cosmetic gloves but are not durable and power is lost during the flexion of the hand with the glove. Currently no commercially available hand provides sensory feedback of the applied force to the user. Amputees have to rely on visual feedback for information surrounding the gripping procedure. All the prehensors posses the ability to maintain gripping force without supplying a control signal which conserves the users energy because the amputee does not have to supply a constant muscle contraction. Most powered hands make use of palmar prehension and consists of a metal frame covered with a soft liner of PVC which is covered with cosmetic glove. Hands have a finger angular speed of about 60 degrees per second and pinch force of between 90 and 130 N.

The *Veterans Administration (VA)* hand(Figure 3-19) include break away fingers which will release the grip under extreme load to protect the hand.[3]

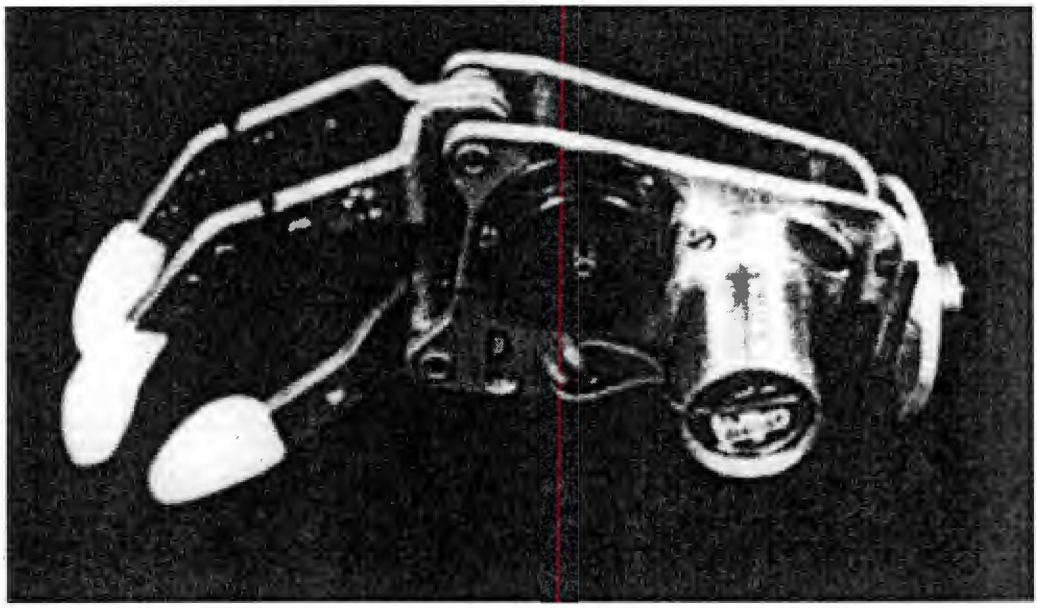


Figure 3-19: The Veterans Administration hand

The *Otto Bock* hand is a simple but the most reliable prosthetic system currently available with parts of the highest quality and precision. The hand developed during the 1960's was aimed at a electromechanical hand meeting the technical and cosmetic demands imposed on it by the user. The hand consists of three main components:

- The hand *chassis* performs the pointed grip performed by the thumb, index and middle finger.
- The *inner* hand, made of soft plastic, provides the form of the hand.
- A cosmetic *glove* reproduce the hands natural external appearance.

The frame for all the models are the same size, with only the size of the plastic surrounding it differing. The two fingers together and the thumb approach each other simultaneously. The ring and little finger contains wire core which is surrounded by plastic and thus couple their movement to the middle finger. Most hands incorporate a back locking system which keeps a constant grip on the object without continuous power application conserving energy. The hand also incorporates a gearshift mechanism which is in low gear when the finger moves freely but switches to high gear as it grips the object to produce a high gripping force. It is not possible to open the hand immediately after is has been gripped tight. The force in the hand has to reach the level where it switches into high gear first. The motor and gear unit uses either a spindle drive or a gear-wheel drive. The hand has a opening width of 100 mm, an average gripping speed of 85 mm/second and a maximum grip force of 80 N. The use of the pliable hand shape over the mechanism gives it better grasping capabilities because the deforming surfaces can accommodate the shape of the object. The hand can be used with most available hand control systems. The battery of the 12 Volt model is stored between the wrist and the stump, forcing the user to remove the hand to recharge the battery. In the 6 Volt model the battery pack is external and interchangeable, making it easy to switch the batteries. The 12 Volt hand develops a pinch force of 90 N and produce no noise. The 6 Volt hand is 20 percent weaker and slower than the 12 Volt model but has a lower power consumption and is smaller size.

The *Steeper hand*(Figure 3-20) is very similar to the design of the Otto Bock hand with inferior performance. The hand consists of the driving mechanism inside a two piece enclosure. The hand has three fingers made of hard plastic with the remaining ring and little finger made of soft plastic and attached to the enclosure. The hand has a single motor, a drive screw and a nut actuator which closes the thumb and the fingers as the nut slides along the screw. This mechanism automatically includes a back locking system and the thumb has a break away function. Some models of the hand use servo motors having output power that is relative to the displacement of a pulling cord.

In the *Hosmer NU-VA* synergetic prehensor two separate motors are used to drive the thumb and index finger simultaneously with one at low speed and the other at high speed. This utilises the advantages of

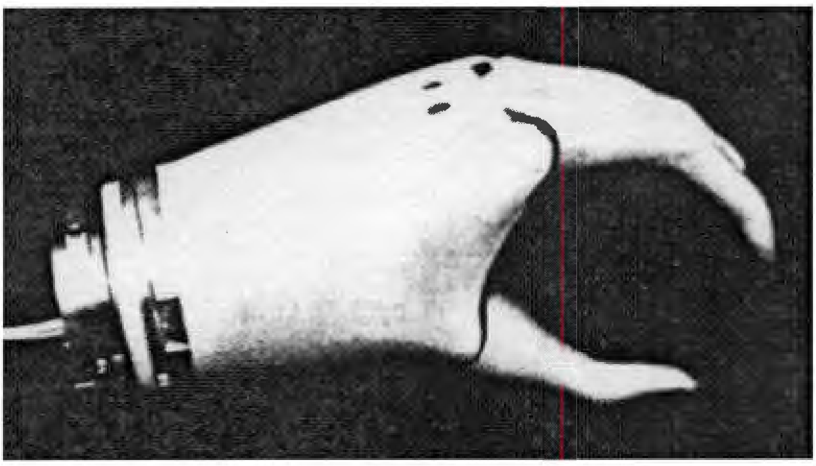


Figure 3-20: The Steeper electric hand.

both features in that it can open and close quickly and still have a high gripping force. Fingers are lined with arrayed neoprene pads. The fast fingers have a back-lock mechanism. The myoelectric control use the mechanical smoothing of the system instead of filtering the signal thus decreasing the response time.

The *VANU* hand is somewhat noisy and look clumsy and heavy. The hand is rugged and delivers the highest pinch force of available hands of 111 N. It has a fully proportional control system with the use of two muscle control sites. The hand has a plastic moulded wrist in which the controls are housed which makes it easily interchangeable but impossible to use with long below-elbow stumps.

The *RIM hand* has two muscle control sites and is one of the most responsive systems. The hand consists of five easily interchangeable modules.

The *UNB* hand works from one control muscle site. The user is taught to contract the muscle in a way to produce signals with different amplitudes. A relaxed muscle puts the hand in the "off" state, while a moderate contraction closes the hand and a strong contraction opens the hand.[3,20]

The *VASI (Variety Ability Systems Inc.)* hands consists of a wide range of hands developed at the Hugh Macmillan Rehabilitation Centre(Figure 3-21). These hands are available in various sizes fitting amputees as young as two years. The hands are myoelectrically controlled by the amputee. These hands are of a high quality and very functional. There is one basic design for all the hands which is scaled down for the different models. The hand has a cosmetic appearance and is powered by 6 Volts. An energy saver circuit is optional and can be added to conserve power consumption of the system. The hand can be controlled using different control schemes including single and double site control The design of the hand is simple and robust making the system very reliable.[13]

Figure 3-21: The VASI myoelectric hand.

3.4.4.2 Hands under development

Most existing prosthetic hands discussed consist only of one degree of freedom and at the most three active fingers. In recent years though, there has been renewed interest in multi-fingered robotic hands for; industrial and prosthetic use, entertainment and the study of human movement. These applications are sometimes very closely linked but do have very distinct differences. The latest progress in medical, material and especially electronic technology has sparked the interest in developing dextrous prosthetic hands. This enables the components of the hand to be smaller, lighter and more energy efficient. Though progress is being made, there are still more ideas than actual practical solutions. Most of these dextrous hands consist of three or more multi-degree-of-freedom fingers mounted on a solid palm. The success of artificial hands depends on the development of suitable mechanisms, actuators and control strategies.[9]

Recent developments include the hand developed at the *Princess Margret Rose Hospital* (Figure 3-22), in Scotland. and the hand developed by Calif, of the *Children's Hospital at Stanford* (Figure 3-23). The latter is a unique non-anthropomorphic gripping device which seems to be functional.[3]

The *Een and Holmgren Systemteknik (ES) hand* (Figure 3-24) is a five-fingered adaptive anthropomorphic hand, allowing flexion in the second and third fingers continuously and respectively until each finger reach an object. This is achieved by wires arranged like tendons. The fourth and fifth fingers are flexed until the second and third fingers are stopped. The thumb opposes the side of the index finger. The hand proved to be inferior to non-adaptive hands in width of grip, grip force and overall performance. Tests showed that a non-adaptive hand was preferred by most users in spite of the slightly better cosmetic appearance provided by the ES hand.[2]

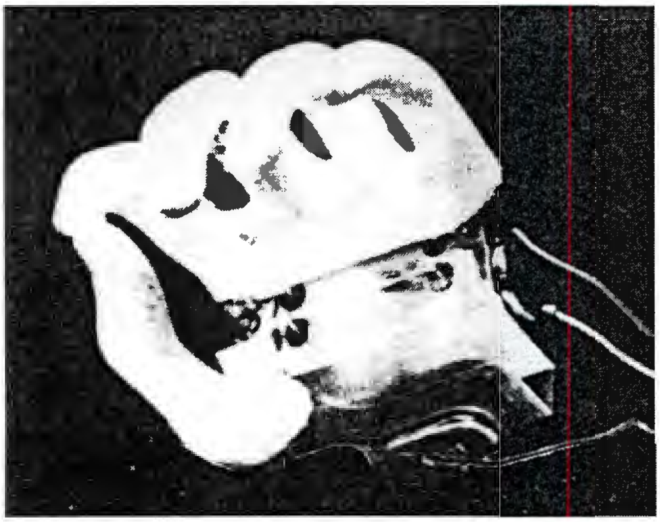


Figure 3-22: The hand developed at the Princess Margret Rose Hospital

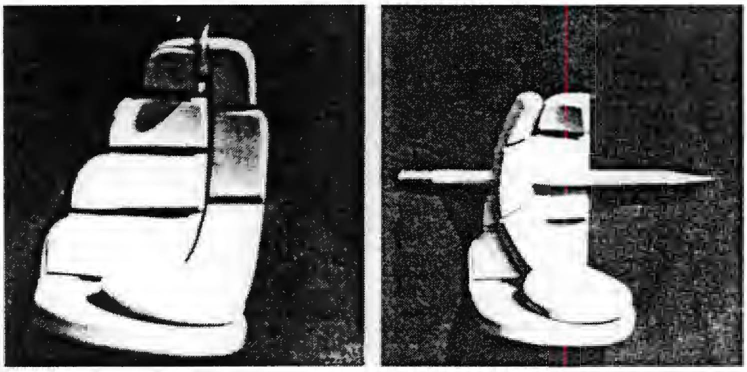


Figure 3-23: The hand developed by Calif.

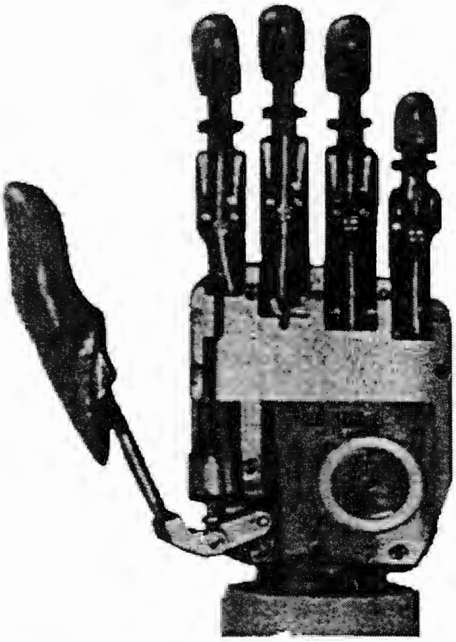


Figure 3-24: The ES anthropomorphic hand.

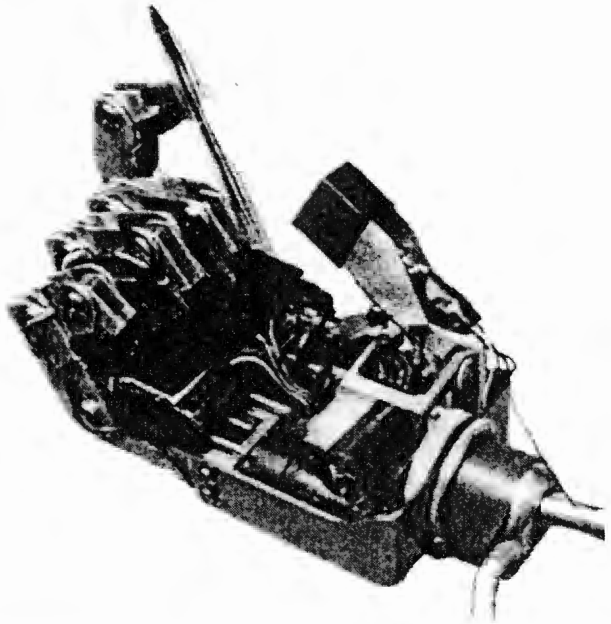


Figure 3-25: The Chappel single degree of freedom hand.

Chappel and Nightingale (1987) fitted a single degree of freedom hand(Figure 3-25) with slip and touch sensors. Together with a micro-controller this improved the function of the hand considerably. This hand was developed further by *Chappel and Kyberd* (1991) into a multi-fingered hand. The hand can be operated by electric motors or pneumatic actuators if an electrical interface exists. The hand is a five-fingered multi-functional hand and due to the easier interface with the electric micro-controller it is driven by four DC motors. It is controlled by the micro-controller receiving information from the position, touch and slip sensors mounted on the hand as well as the EMG input from the antagonistic muscles. The hand consists of an aluminium palm block, two motors with gear boxes driving the thumb and two motors and gear boxes driving the first finger and the last three fingers as a group. The four fingers have three joints for flexion and extension through a pre-defined trajectory, with no adduction or abduction. The thumb is solid with one two degree of freedom joint allowing flexion and extension as well as adduction and abduction. The fingers only stop when the finger tip stops moving or when the maximum flexion for the digit is reached. The last three fingers are equipped with a differential mechanism which enables each digit to stop individually after it has made contact with the object while the others are able to continue moving. Touch sensors are mounted on the palmar side of the four digits as well as on the lateral side of the index finger. The tip of the thumb is equipped with combined touch and slip sensors. Two potentiometers are placed at the base of the thumb and one each at the base of the index and third finger. A programmable controller is used to ensure adaptable control functions and adjustments to be made. All motors are supplied by 12 Volt and the fingers are driven by 7:2:1 gearboxes except the thumb which is driven by a 12:8:1 gearbox.[20]

Kyberd and Chappel (1994) developed another dextrous hand using the same principles as the previous hand. For this hand it was determined that four degrees of freedom is essential for an anthropomorphic hand:

- Flexion/extension of index finger
- Flexion/extension of thumb
- Abduction/adduction of thumb
- Flexion/extension of the last three fingers as a group

The Southampton Adaptive Manipulation Scheme (SAMS) was developed to control the hand. This is a hierarchical control which allows a larger number of independent motions to be controlled with a smaller degree of user input.[23]

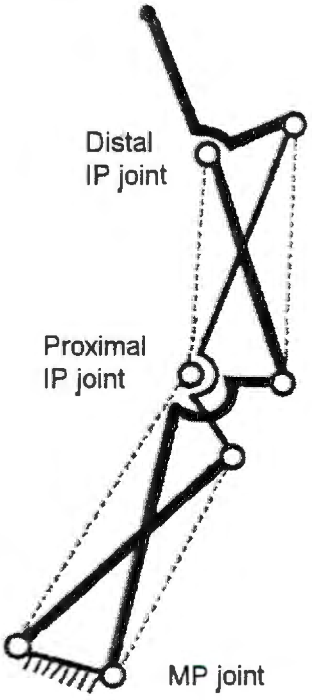


Figure 3-26: The six-bar finger mechanism.

Research by *Guo* (1993) concerns the design of a three-jointed, anthropomorphic, finger mechanism. The finger is a single degree of freedom, six-bar linkage system. The dimensions of the mechanism are determined by a vector analysis approach. The effect of joint friction on the transmission efficiency is established. A mathematical model of the gripping configurations is developed by measuring joint positions of a human finger. Non-linear programming, using motion posture and locus as well as transmission efficiency and weight as the objective functional, was incorporated to solve for the optimal parameters of the mechanism. The functional is subjected to geometric and bionic constraints and numerically optimised to determine the dimensions for the finger. The problems encountered earlier with a five-bar mechanism like larger elastic displacement during grasping, complex structures and non-anthropomorphic grasping motion are eliminated by the six-bar design. The basic design of the mechanism is shown in Figure 3-26. All the fingers of the hand except the thumb have similar operating configurations, making it necessary to model only one finger. The motion of the hand was studied thoroughly and relation ships were determined to serve as constraints for the optimal formulation. The grasping trajectory of the finger was divided into pinching and holding. Constant functional relationships between the three segment angles and the finger tip displacements were determined for these trajectories. The pinching is the initial motion to pinch objects, with the angle of the first joint varying between 5 and 42.5 degrees, while the holding range is the additional bending of the finger to hold objects, with the angle of the first joint varying between 42.5 and 80 degrees as shown in Figure 3-27.[10]

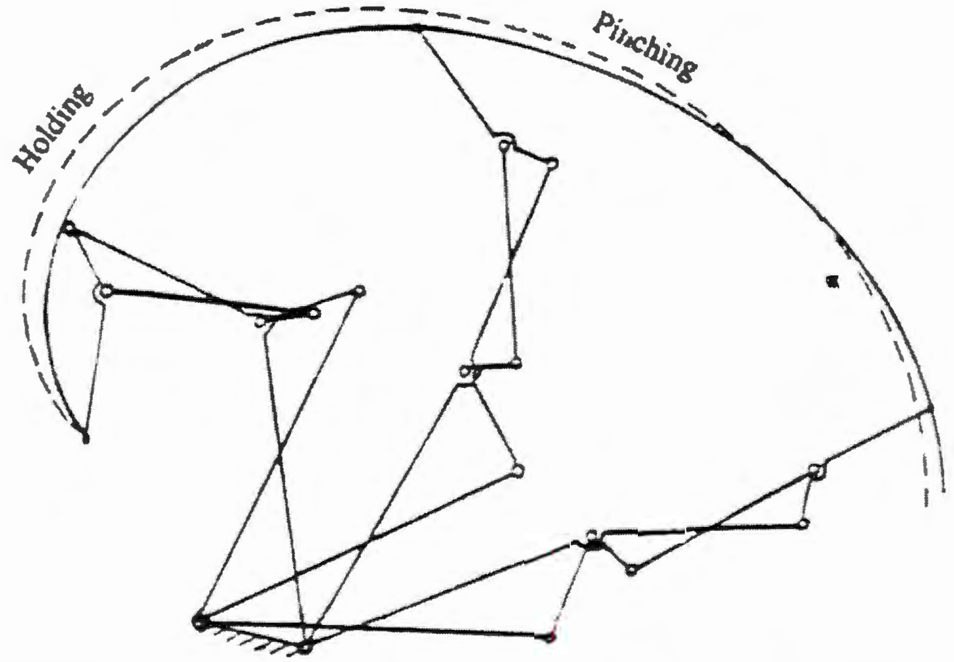


Figure 3-27: The difference between the pinching and holding trajectory.

The hand developed by *Crowder* (1991) consists of four mechanically adaptive fingers and a jointless thumb. The end effector has the ability to adapt to the shape of the object. The addition of touch and slip sensors to the prosthetic hand has proved to increase the dexterity considerably without an increase in conscious effort from the user. The palm and the fingers of the hand together have twenty degrees of freedom. The knuckles have two each, one each at the remaining joints , three in the thumb and one in the palm. It is been determined that for a dextrous hand to achieve a flexible system it only needs three fingers and a palm structure. The motion of the two distal joints of the finger are assumed to be coupled, reducing it to one degree of freedom. The maximum relative movement between joints are taken as 90 degrees. The thumb is constructed to allow tip-to-tip pinch with the index finger only when the plane of pinch is perpendicular to the surface of the palm. The hand is driven by three brushless DC motors for the thumb, the index finger and the remaining three fingers as a group. Together with high ratio harmonic gear boxes it ensures high power, small size and good reliability. The hand has a 49 N grasp force and 30 N pinch force. A differential mechanism giving independent movement between the finger sections and the knuckle is used for each finger. The fundamental operating system for the finger is based on the equalising bar shown in Figure 3-28. The

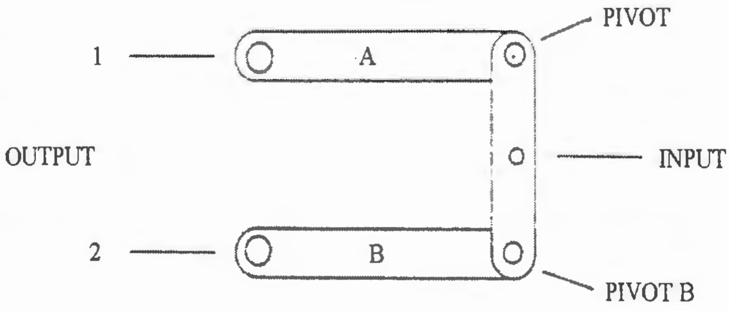


Figure 3-28: The equalising bar system.

principle of the bar is the same as a differential; the sum of the output forces from the bar is equal to the input force to the bar. This causes the input forces to be distributed according to the resistance applied to the output. The same principle is used to drive the last three fingers semi-independently with one motor. This ensures that at least three fingers of the hand always make contact with the object. Two optical reflective touch sensors were placed in the thumb, one on each finger tip except the last finger and six sensors on the upper surface of the palm.[4]

The *Rehabilitation Institute of Montreol* and Ecole Polytechnic is developing a multi-articulated hand (Figure 3-29) which has considerable potential. The hand has five fingers and is driven by one motor situated in the palm. The hand is designed to perform specific prehension patterns. This is made possible by the exploitation of the optimal position of the thumb. All the fingers can articulate at two joint levels and are adaptable to conform to the shape of the gripped object. The thumb is articulated at carpometacarpal joint and can be positioned to perform lateral and tridigital prehension pattern. The hand reduces the pre-positioning of the arm to enable good grip considerably and allows good visibility of the object.[13]

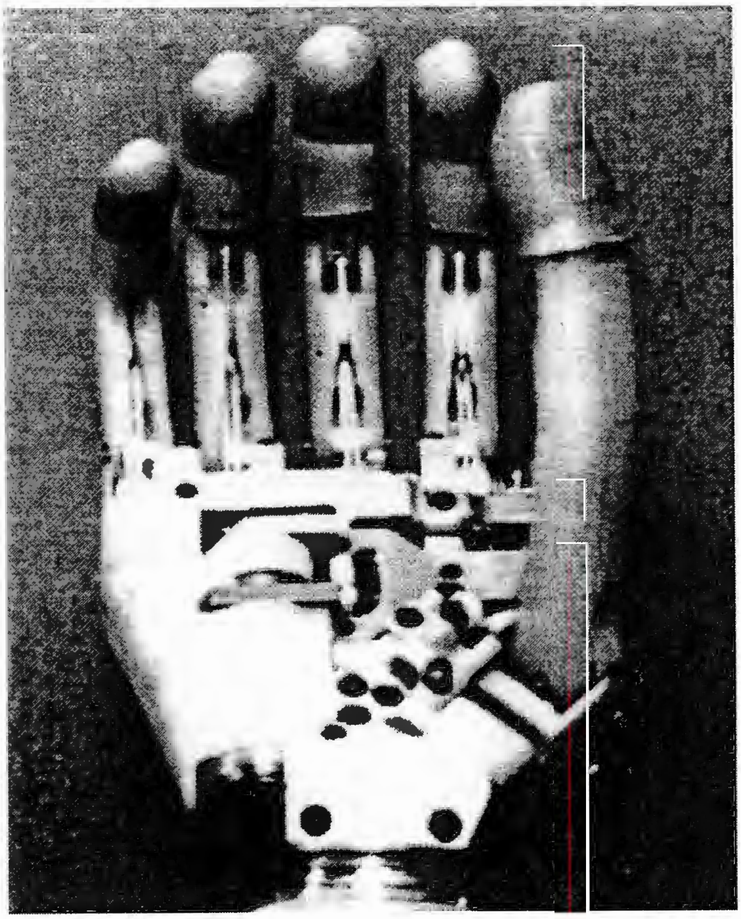


Figure 3-29: The Montreol multi-articulated hand.

3.4.4.3 Single DOF hands versus Dextrous hands

Commercially available anthropomorphic hands usually consists of a single-degree-of-freedom precision grip. The disadvantages involved with these hands are that it is not possible to open wide enough to grasp large objects and does not flex far enough to grip small items in a power grip. Fortunately, humans are very adaptable and learn quickly how to overcome the shortcomings of these single-degree-of-freedom hands. These disadvantages can be overcome by the anthropomorphic hand because of the wider range of motion and the additional degrees of freedom added to it and thus make it more functional and give a more steady grip. Dextrous hands are also more cosmetic and have more natural gripping trajectories but are heavier, more difficult to use, have low operational safety, a short working life, a high energy consumption and an increased manufacturing expenditure.[23,26]

3.4.5 Wrist units

Wrist units can sometimes be part of the hand but are mostly a separate component. The main functions of the wrist is to provide an attachment between the terminal device and the forearm of the prosthesis and preposition the terminal device before use. The units should be as thin as possible and vary from round to oval in shape as shown in Figure 3-30 and should be possible to fit to most commercial hands. Wrist units are divided into; friction, quick-change, rotational and ball and socket units.[3]

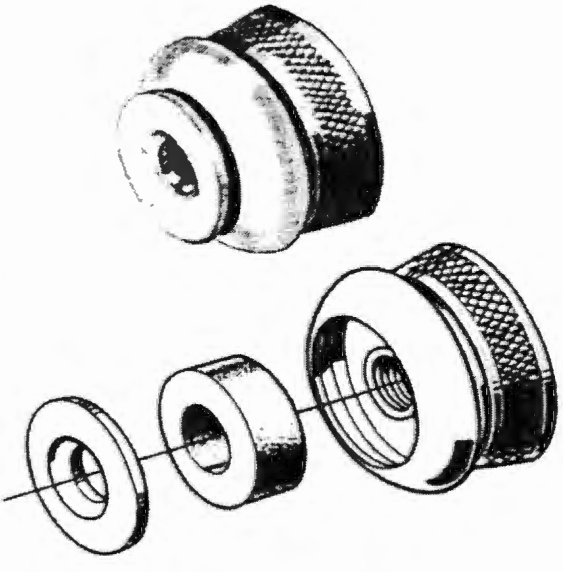


Figure 3-30: The standard configuration of a wrist unit.

3.5 Control of prosthetic hands

During the control of prostheses input from the environment is conveyed directly to the user through the various senses or to the prostheses. This information is analysed and the prosthesis either reacts directly on this information or on an input signal from the user until further input from the user or the hand itself. Desirable attributes of prostheses control are:

- Low *mental loading* or subconscious control.
- Independence from control of *other systems*.
- Various functions must be *co-ordinated* simultaneously.
- All functions should be directly *accessible* with the shortest time delay.
- The device should not hamper normal body *activities*.
- It must have a natural *appearance*.
- It should have a proper *feedback* system.

There are several variables that should be controlled or monitored including;

- Position
- Velocity
- Prehension force
- Touch
- Shape
- Texture
- Temperature

Input control to prostheses come directly from muscles, indirectly through joints or as by-products from muscular contractions. They can be classified as follows:

Biomechanical:

- Movement from joints
    - Chin and head
    - Glenohumeral flexion/extension or adduction/abduction
    - Biscapular and scapular abduction
    - Shoulder elevation and depression
    - Chest expansion
    - Elbow and wrist movement
- Direct from muscles
    - Tunnel cineplasty
    - Skin that is adherent to underlying muscle
    - Long transradial amputation

Bioelectric/acoustic:

- Myoelectric
- Myoacoustic
- Neuroelectric [3]

3.5.1 Control signals

3.5.1.1 Switch control

Switch control is the simplest and least expensive control system. It can either be used mechanically to lock or unlock joints or electrically to control actuators. Two switches are often used for the bi-directional control of an electric motor or single direction switch can be used in a three-state control system, both of which are described later in Section 3.5.2.1.[29]

3.5.1.2 Myoelectric control

In the 18th century *Luigi Galvani* identified the existence of electrical activity in muscles. The study of EMG got a boost in the 1940's with the advent of more sophisticated circuitry. The principle of EMG is the detection of action potentials created by the motor end plates of nerves on the muscle fibres. The action potential is transmitted along the neurons by means of sodium-potassium pumps which cause the exchange of ions and leads polarisation and the depolarisation of the membrane. This potential reaches the motor endplate on the muscle fibre and causes a depolarisation of the post-synaptic membrane. The latter triggers the release of Ca^{2+} which cases the opening of binding sites between the actin and myosin and therefore the utilisation of ATP (Adenosine Triphosphate), the release of energy and the relative sliding of the actin and myosin. The depolarisation of the muscle cell membrane just before muscle contraction produce a measurable potential in the surrounding tissue and tissue fluids. The individual electric signal of a nerve is called a *motor unit action potential* (m.u.a.p.) and the detection thereof is called deep EMG. This is not used to control prosthesis because it is an invasive procedure, produces a localised signal, is very difficult to control by the user and is prone to dislocation and bleeding. The electric signal used in prostheses is the combined signal from various motor neurons of a muscle group and is called surface EMG. Experiments done in 1952 showed that the relationship between the force applied by a muscle and the EMG produced is almost linear. The signal has a wave form due to the potential wave moving towards the electrode and then away from it. The muscle groups are selected in which all perform essentially the same function. The signal is detected by electrodes placed inside the socket making contact with skin above the particular muscles. Electrodes are normally made of stainless steel or gold and function as an antenna using the body's perspiration as a conducting gel to the skin. The signal produced is about 1/70,000 of a volt and has to be amplified for further use. Specialised circuitry has been developed during the years for the capturing of the EMG of specific muscle. Important factors to control are:

- Gain and dynamic range
- Input impedance
- Frequency response
- Common-mode rejection

The ideal is to isolate the signal generated by the muscle from all other noise or artifacts. The gain of the system is the factor with which the original signal should be amplified to have a useful output signal. The maximum amplitude of indwelling EMGs are higher than surface EMGs therefore needing a smaller gain. The selected gain depends on the use of the output signal. The electrode-skin interface has a high finite impedance. Indwelling electrodes have a higher impedance because of the smaller area. To ensure that the voltage drop over the electrodes is smaller than the EMG voltage the input impedance of the system should be quite high, at least 1MΩ. The frequency response determines the upper and lower frequencies, the bandwidth, between which the signals are to be let through to ensure the all frequencies in the actual EMG signal is captured and everything outside this range rejected. Both the boundaries are higher for indwelling than surface electrodes. Notch filters can be used to filter certain known disturbing frequencies. The body is a good conductor that easily picks up radiation. To reject these frequencies a third ground node is introduced. The amplifier amplifies the difference between the potential at each electrode. The disturbances are equal at both the original electrodes which means it is cancelled when subtracted. The ability of a system to reject external disturbances is called *common-mode rejection ratio* (CMRR). This raw signal is very spiky and has both positive and negative values and must therefore be processed further to produce a useful signal. These signals are used in different control strategies to control prosthesis. The different strategies involves different circuitry as indicated in Figure 3-31.

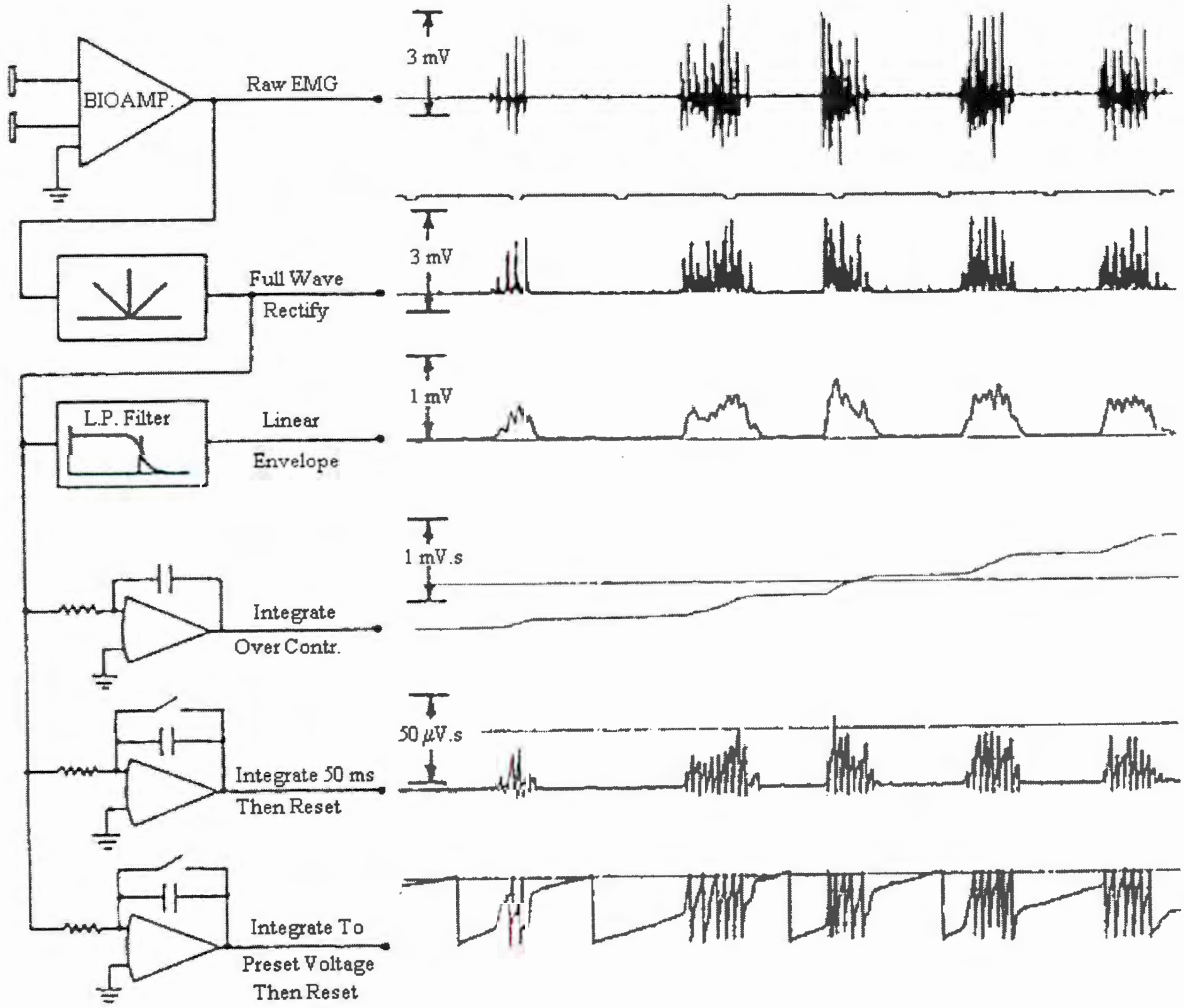


Figure 3-31: Various methods of processing EMG signals.

The most common types of on-line processing includes:

- Half- or full-wave *rectification* (absolute value)
- Linear *envelope* detector (Half- or full-wave rectification followed by a low-pass filter)
- *Integrate* full-wave rectified signal over *entire period*
- *Integrate* full-wave rectified signal for a *fixed time period*
- *Integrate* full-wave rectified signal to a *present level*

The use of myoelectric control leads to specific advantages and disadvantages which have to be considered in the designing process.

Advantages:

- The hand provides improved *cosmesis.*
- It is very *functional* for doing light work.
- Below-elbow amputees need no *harnessing.*
- It provides superior *pinch force.*
- The close socket fit and the natural use of the muscles provides *feedback.*
- The socket can be fitted to any *stump length.*
- The system provides the possibility for improved development in the prostheses.

Disadvantages:

- The hand is highly susceptible to *water and sand.*
- The *functionality* of the hand is highly dependant on the quality of the socket fitting to detect the myoelectric signals. Contact between the electrodes and the skin must be maintained at all times.
- The hand is *fragile* due to the complex components.[12,26,40]

3.5.1.3 Myoacoustic signals

Contracting muscles produce acoustic sounds that can be recorded with a standard microphone. This method is known as acoustic myography (AMG). This was discovered in the 19th century but has not been used until recently. There is a linear relationship between the sound amplitude and the isometric force in the muscle. The microphone produce a 50 mV potential to be amplified further. The signal is band-passed filtered, centred at about 25 Hz and is then full-wave rectified and filtered with a time constant of about 0.2 second. The circuit is fitted with a high-amplitude and variable-delay signal eliminator.

Advantages:

- *Direct contact* with the skin is not necessary to produce a signal.
- *Skin impedance* changes have no effect on the signal.
- The signal is less sensitive to the precise *placement* on the muscle.

- The *output signal* of 50 mV requires less amplification and electrical shielding.
- Acoustic transducers can be *caste* into desirable shapes for better results.

Disadvantages:

- *Extraneous noise* especially that of low frequency can affect the signal. Ways of avoiding this problem is introducing band-pass filters or a second microphone to serve as a reference signal.
- The *insensitivity to specific placement* on the muscle can make it difficult to distinguish between different muscles.
- *Adopting AMG control* from predominantly excising EMG systems leads to initial manufacturing costs. These costs are relatively cheap compared to excising systems.[1]

3.5.1.4 Neuroelectric control

Micro-electrodes interfacing directly with nerves or neurons are still under development. The possibilities of such a system for further development in prostheses are endless. It would be like substituting what is lost of the hand with the prosthesis and plugging it into what is left of the hand. One of the greatest draw backs at this stage is the interfacing between the nerves and electrical system and the skin penetration thereof without rejection by the body. Other methods are to surgically connect the desired nerves to redundant muscles (replacing the lost muscle) and using these sites to pick up myoelectric signals. Another idea under development is detecting brain waves and using them as signals. The complexity of this method compared to existing technology makes its use impractical but it might be a future possibility.[3]

3.5.1.5 Other control methods

Phonosensorial control uses various acoustic patterns from the throat during speech as control signals . *Myosensorial* control uses the change in muscular volume as control. It is difficult to confine this signal to a specific muscle group.

3.5.1.6 General comments

Before any amputee can be fitted with a prosthesis a decision must be made as to what type of control will be used for the prosthesis. The choice of control system is determined by the user's preference, financial ability, occupation and social surroundings. Though the latter may seem to be of minor importance research has shown that the amputee's social surroundings effects the choice in prostheses considerably. The availability of technology as well as the state and level of amputation and the strength of the remaining limbs also affect the choice of control system.

3.5.2 Control strategies

Different motions in a system with more than one control are normally achieved through sequential rather than smooth motions to make it easier for the user.[14]

3.5.2.1 Commercial strategies

For body powered prostheses the contraction of the muscles are directly used as control. Additional switches can be activated by other parts of the body to lock and unlock joints in specific positions. A *single direction* three-state electrical switch can be used in various ways to control different prostheses. Figure 3-32 represents the control for an electric hand with the first state closing the hand, the second state closing the hand and the in-between states locking the hand in that position. Two switches, connected as shown in Figure 3-33 are often used for the *bi-directional* control of an electric motor.[3]

1. Normal rest position, amputee relaxed, no tension on switch	1. Hand remains locked.
2. First active position, position must be maintained by the amputee, if relaxed switch will return to position No. 1.	2. Hand closes continuously while switches in this position.
3. Neutral position requiring additional excursion.	3. Hand stops closing and locks.
4. Second active position reached by additional excursion.	4. Hand opens when in this position.
5. Neutral position requiring additional excursion. End point is a stop that transmits force to the control cable.	5. Hand stops opening and locks.

Figure 3-32: The single direction three state electric switch and the general use of the of the various switch positions.

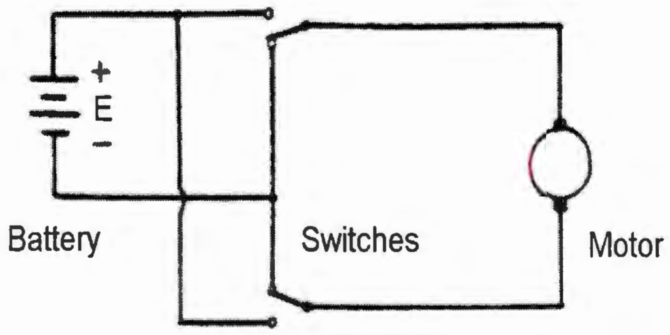


Figure 3-33: The basic circuitry for a bi-directional electric switch.

Myoelectric control is used in various ways to control prostheses. It can be used on a *single input* from the muscle site with one threshold level or with two threshold levels. With the two levels one is used for closing and the other for opening the device. A *double input* signal is also used on two antagonistic muscle sites (Figure 3-34) where the difference between the signals are used to open or close the device. The selection of the method depends on the state of the individuals residual muscles and the ability to be controlled. Further myoelectric signals can be used *digitally* where a threshold level is used to switch the actuator on or off. With *proportional* control the signal is constantly measured and the closing speed or force in the hand is controlled to be proportional to the signal. This method has a few practical drawbacks but tests showed it is preferred by users for its quickness, control of speed and force and decreased muscle effort.[32] Table 3-1 presents a summary of the most popular commercial control systems used for prostheses.

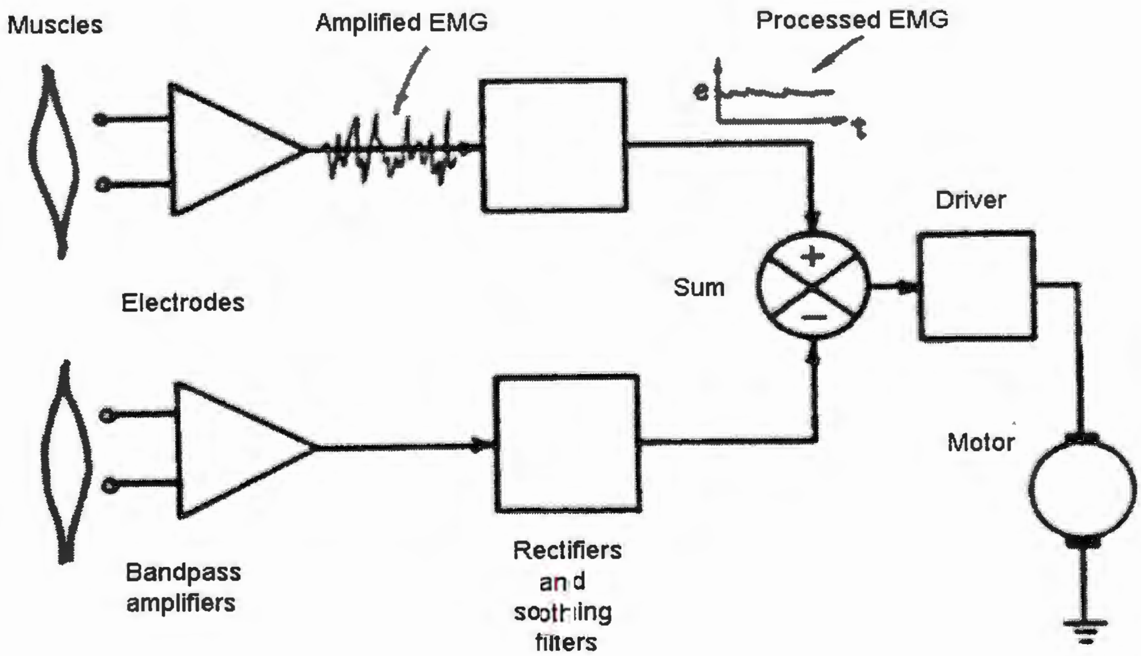


Figure 3-34: Using two muscles for electromyographic control

Switch Control techniques of powered upper-limb prosthetic systems

- Unilateral below-elbow systems
  - A. Powered hand/hook
    - 1. Hand/hook control
      - a. Biscapular abduction
      - b. Chest expansion elbow
      - c. Humeral flexion
- II. Unilateral above-elbow systems
  - A. Powered hand/hook-conventional elbow and lock
    - I. Hand/hook control
      - a. Shoulder elevation
      - b. Chest expansion
    - 2. Elbow control
      - a. Humcral flexion
      - b. Biscapular abduction
    - 3. Elbow-lock control
      - a. Shoulder abduction/humeral extension
  - B. Conventional hand/hook-powered elbow
    - 1. Hand/hook control
      - a. Humeral flexion
      - b. Biscapular abduction
    - 2. Elbow control
      - a. Shoulder elevation
      - b. Chest expansion
      - c. Shoulder abduction/humeral extension
  - C. Powered hand/hook-powered elbow
    - 1. Hand/hook control
      - a. Hummal flexion
      - b. Biscapular abduction
    - 2. Elbow control
      - a. Shoulder elevation
      - b. Chest expansion
      - c. Shoulder abduction/humeral extension
- III. Unilateral shoulder-disarticulation system
  - A. Powered hand-conventional elbow and lock
    - 1. Hand/hook control
      - a. Chest expansion
      - b. Shoulder elevation
    - 2. Elbow control
      - a. Biscapular abduction
      - b. Shoulder elevation
    - 3. Elbow-lock control
      - a. Shoulder elevation
      - b. Nudge control
  - B. Conventional hand/hook-powered
    - 1. Hand/hook control
      - a. Biscapular abduction
      - b. Shoulder elevation
    - 2. Elbow control
      - a. Shoulder elevation
      - b. Chest expansion
  - C. Powered hand/hook-powered elbow
    - 1. Hand/hook control
      - a. Biscapular abduction
      - b. Shoulder elevation
    - 2. Elbow control
      - a. Shoulder elevation
      - b. Chest expansion
- IV. Unilateral interscapulothoracic systems
  - A. Powered hand/hook-conventional elbow and lock
    - 1. Hand/hook control
      - a. Chest expansion
      - b. Uniscapalar abduction
    - 2. Elbow control
      - a. Uniscapular abduction
      - b. Lateral trunk bending
    - 3. Elbow-lock control
      - a. Chest expansion
      - b. Nudge control
  - B. Conventional hand/hook-powered elbow
    - 1. Hand/hook control
      - a. Uniscapular abduction
      - b. Lateral trunk bending
    - 2. Elbow control
      - a. Chest expansion
      - b. Uniscapular abduction
  - C. Powered hartd/hook-powered elbow
    - 1. Hand/hook control
      - a. Uniscapular abduction
      - b. Chest expansion
    - 2. Elbow control
      - a. Chest expansion
      - b. Uniscapular abduction
      - c. Lateral trunk bending

Myoelectric control techniques of powered upper limb prosthetic systems

- I. Unilateral below-elbow systems
  - A. Powered hand/hook
    - 1 . Hand /hook control
      - a. Forearm extensor muscles-open hand
      - b. Forearm flexor muscles-close hand
- II. Unilateral above-elbow systems
  - A. Powered hand/hook-conventional elbow and lock
    - 1. Hand/hook control
      - a. Triceps-open hand
      - b. Biceps-close hand
    - 2. Elbow control
      - a.. Humeral flexion
      - b. Biscapular abcuction
    - 3. Elbow-lock control
      - a. Shoulder abcuction/humeral extension
      - b. Shoulder elevation
      - c. Chest expansion
  - B. Conventional hartd/hoak-powered elbow
    - 1 . Hand/hook control
      - a. Humeral flexion
      - b. Biscapular abduction
    - 2. Elbow control
      - a. Triceps-extend elbow
      - b. Biceps-flex elbow
  - C. Powered hand/hook-powered elbow? (three-state myoelectric control)
- III. Unilateral shoulder-disarticulation systems?
- IV. Unilateral interscapulothoracic systems?

Table 3-1: The most common prosthetic control systems used by amputees.

3.5.2.2 Strategies under development

For normal grasping in a human hand, information is gathered by different body senses. This information is fed back to the nervous system to co-ordinate the muscles contractions to perform the necessary movements. When the object is in the hand feedback loops are used to control it. This basic hierarchical control of the central nervous system (CNS) can be broken down into three layers:

- *Lower level*: force and position
- *Intermediate level*: shape and force reflexes
- *Top level*: conscious strategic hand control[12]

The challenge for the designer of a artificial device lies in the high performance of the human hand. This can only be achieved by a complex arrangement of linkages, power sources, clutches and brakes. This is the reason why commercially available hands tend to be unsophisticated, lightweight and durable. The lack of sufficient space is one of the biggest problems facing the designer. Currently all the devices need to perform the same complex functions as the human hand can not be fitted into a life-size artificial hand. The hope for the future rests heavily on the effective use of low cost programmable electronics to mimic the control of the hand. The same hierarchical control as in the human hand can be used to open and close the hand while the controller determines the necessary digit-control functions. This is similar to the lower level of control performed by the spinal cord.

The current tendency is to determine the main hand shapes used by the hand during normal grasping. The micro-controller is used to preposition the hand into these shapes according to the shape of the object and then to grip the object on the user's signal. The selection of hand shapes and the loops and signals used to control them varies from one strategy to the other. The operation of the hand can be divided into static (gripping) or dynamic operations (manipulations). Most control strategies only concentrate on gripping due to the complexity of manipulation of the object when already in the hand. It is desirable not to only control the initial grip of the hand but to constantly monitor the grip to ensure it does not fail. Different control strategies have been developed by researchers of which most are not used in prosthesis but robotic hands. The principles of these robotic controls form the basis for the controls of prosthetics and are therefore included in the literature. The hand shapes developed by the various researchers and the categories into which they are divided follow the same basic trends but the different schemes are difficult to compare though because researchers use different notations for the various hand shapes and categories. Without adequate pictures it is not always exactly clear from the notation what the specific hand shapes present. To ensure these schemes are presented correctly the original notation referred to for each scheme is maintained.

Chappel and Kyberd (1991) determined seven basic hand shapes used for grasping:

PRECISION:

- P0: gripping a pen.
- P1: between thumb and index finger with the other fingers flexed.
- P2: between thumb and index finger with the other fingers extended.

POWER:

- Fist: gripping large cylindrical objects.
- Small fist: gripping small cylindrical objects.
- Side: between thumb and side of index finger.
- Flat hand: flat hand with thumb on the side

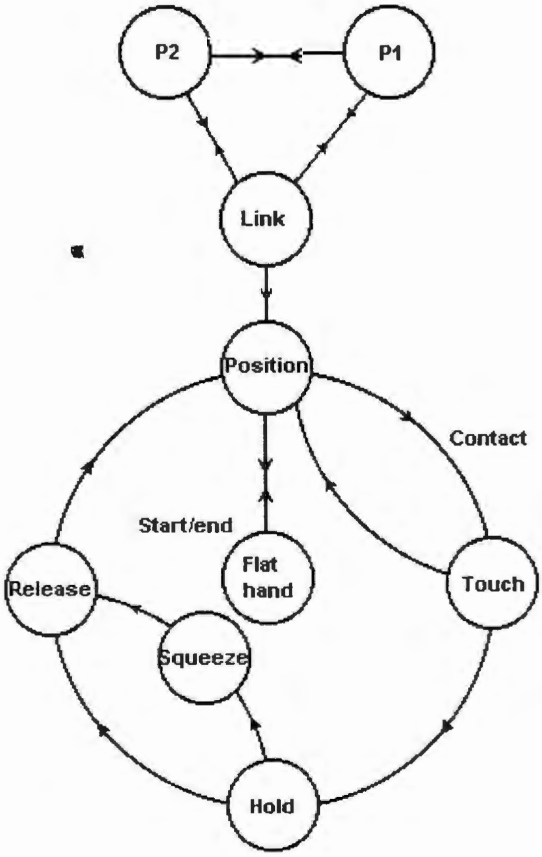


Figure 3-35: The schematic representation of the control system.

Figure 3-35 represents the flow diagram for the control of the hand. The user selects a hand procedure by sending flexion and extension signals which occur in natural progression to the micro-controller. The hand waits for further signals from either the user or the sensors on the hand to determine the mode of closure. When closed around the object the controller either waits for a signal from the user to squeeze the object further or to release the object. Slipping of the object while gripped is detected by the sensors on the thumb and will automatically switch the hand into the squeeze motion. The spacing of the sensors on the hand are shown in Figure 3-36. Touching of the base sensors while in the position state leads to an immediate change into the fist posture and awaits further information. Equally, touching of the side sensors on the index finger will lead to a change into the side posture.[20]

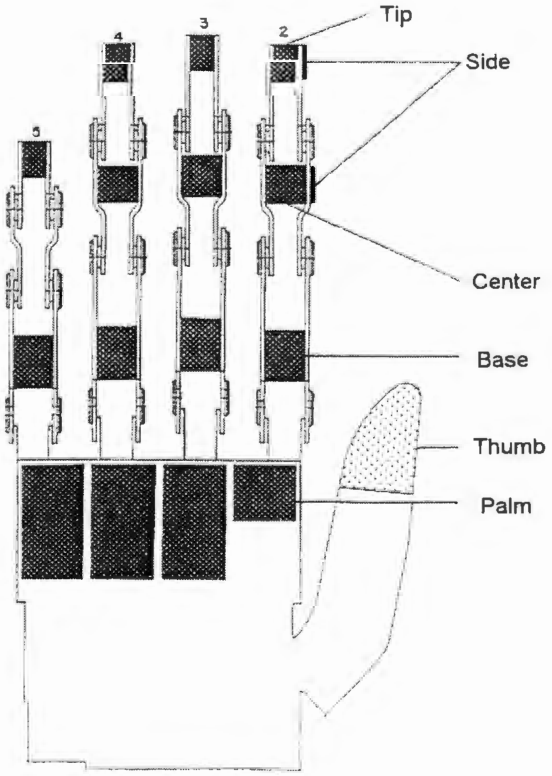


Figure 3-36: The positioning of the sensors on the hand.

Kyberd and Chappel (1994) developed a control strategy is referred to as the Southampton Adaptive Manipulation Scheme (SAMS). The SAMS system was developed to restore the lower and intermediate levels of hand control. The degree of opening is proportional to the muscular tension. Three main prehension patterns performed by an anthropomorphic hand were determined as:

PRECISION: between thumb and index finger.
POWER: between all fingers, palm and thumb.
SIDE: between thumb and side of index finger.

Slip detection is accomplished by vibrotactile sensors detecting vibrations due to sliding and by pressure sensors measuring a sudden change in contact force between the fingers and the object. During slip the normal force between the slipping surface and the object decrease due to the lower dynamic coefficient of friction.[23]

Wren and Fisher (1995) determined four types of task-specific hand shapes(Figure 3-37). The shape choice depend on the geometry of the object. These hand shapes can be closed using one of two modes of digit closure (Figure 3-38):

HAND SHAPES:

- *Precision:* between the tip of the thumb and that of the remaining fingers.
- *Lateral:* between the thumb and the side of the index finger.
- *Manipulation:* best shape for manipulating an object.
- *Hook:* holding a suitcase.

MODES:

- *Distal trajectory:* available for all hand shapes
- *Proximal trajectory:* available for all hand shapes except the hook shape.[41]

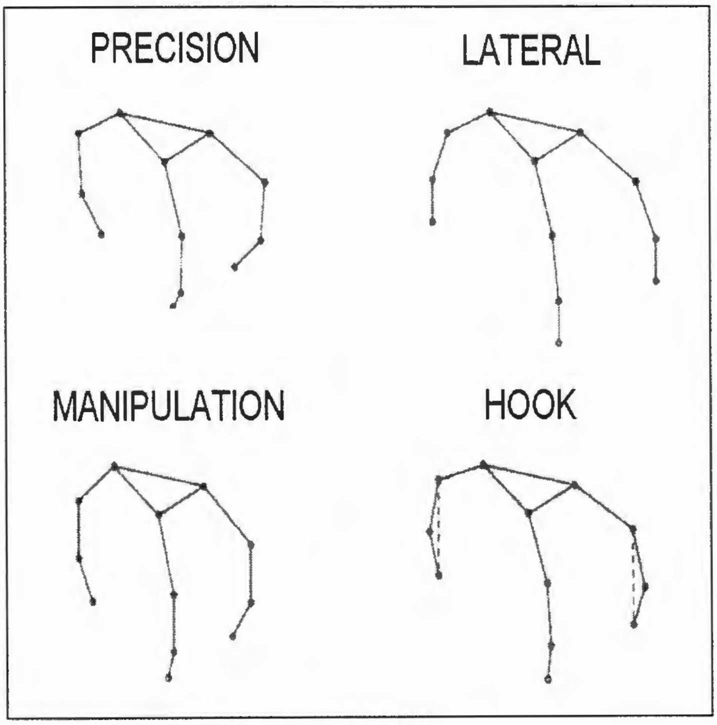


Figure 3-37: The different hand shapes.

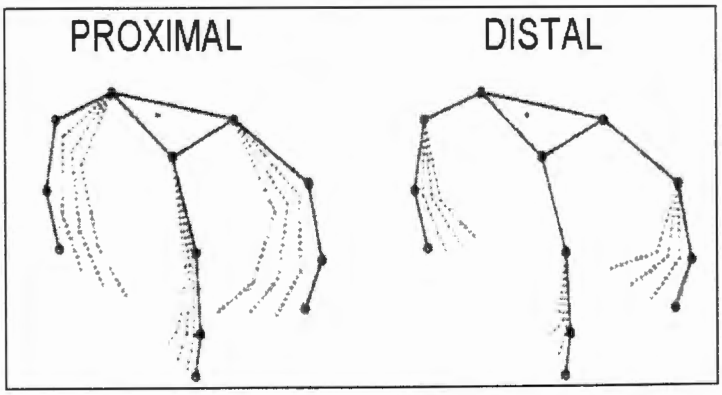


Figure 3-38: The two different hand modes.

Schleshingert (1919) characterised static gripping functions into six basic hand configurations:

PRECISION:

- *Tip:* pinching a small object between the finger and the thumb tips.
- *Chuck:* grasp used when holding a pen.
- *Lateral:* between the thumb and the side of the index finger.

POWER:

- *Cylindrical:* gripping a cylindrical object.
- *Spherical:* gripping a spherical object.
- *Hook:* holding a suitcase.

Crowder (1991) developed a control system with three basic levels. *Level 1* contains the basic motor speed and torque control loops with provision being made for touch sensing. *Level 2* consists of the main hand control algorithms that interpret the users commands to determine the required hand motions. *Level 3* takes the operators commands and converts them into the required input for the second level. Three basic operating configurations were determined:

- *Touch:* causes the first finger to move.
- *Pinch:* moves the thumb and index finger in opposition.
- *Grip:* moves the thumb and all the fingers for the cylindrical power grip.

Al these modes can be cancelled at any time by the *relax* mode, which on demand of the user will open the hand. The hand is controlled by the operator by means of six buttons controlling the three degrees of freedom and two buttons increasing or decreasing the grip force.[4]

3.5.3 Sensory feedback

3.5.3.1 Sensory feedback in the human hand

The human limb can be divided into three layers each containing different receptors. The receptors of the hand can therefor be divided into three layers each with different functions.

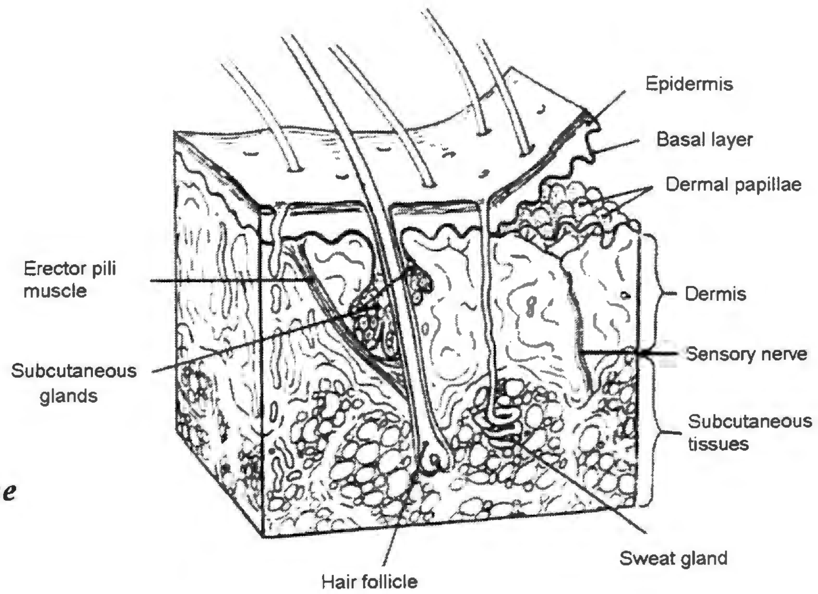


Figure 3-39: The three layers of the human tissue.

Internal Receptors

Motor control of the body parts involves the control of antagonistic muscle groups around the joints connecting them. These muscle groups modulate the stiffness at the joints. There are four types of internal receptors:

- *Neuromuscular spindles* sense the degree of muscle stretch in the muscle fibre, providing precise movement control for the reflective cohesion of the skeleton. They are divided into groups sensing either high or low frequencies.
- *Golgi organs* measure the degree of stress in the muscle fibre at very low response at the muscle-tendon interface.
- The *artificial surfaces* of the joints produce signals proportional to the extreme position, velocity and ligament tension at the joints.
- The *Ruffini corpuscles* are thermal receptors sensing kinematic forces and accelerations.

Dermal Receptors

This is the layer beneath the epidermis and contains the following receptors:

- *Meissner corpuscles* are perpendicular to the surface and responds to a light touch stimulus. These cells are specialised high frequency transducers.
- *Pacinian corpuscles* responds to accelerating mechanical displacements. It is therefore sensitive to vibrational pressure but not to direction.

Epidermal Receptors

These receptors are located in the outermost layer of the skin and respond to external stimuli representing the interactions between the skin surface and the gripped object. There are two types of epidermal receptors:

- *Merkel disks* have a large bandwidth and can respond to compression and shear stimuli.
- *Free-ended nerve fibres* respond to a variety of stimuli, including temperature.

The *dermal* and *epidermal* receptors in the body are important for the design of the hand since it provides *tactile* feedback from the object during contact. The *internal* receptors provides mainly *proprioception* of the joints and some *tactile* feedback. The epidermal receptors are situated in the skin of the body and the sensitivity of the skin varies on different parts of the body. The functionality of the human receptors are extremely high, mainly due to the quick response, high resolution and the variety of modalities which are detected. The sensitivity of the receptors vary with location on the body and is very sensitive in the hand especially the fingertips because of its high functionality. Table 3-2 presents some of the performance specifications for the various receptors on the finger tips.

Frequency response	0 - 400 Hz
Response range	0 - 100 g/mm^2
Sensitivity	± 0.2 g/mm^2
Spatial resolution	1.8 mm
Signal propagation	Motor neurons: 100 m/s Sensory neurons: 2 - 80 m/s Autonomic neurons: 0.5 - 15 m/s

Table 3-2 Sensory specifications of receptors on the fingertip.

3.5.3.2 Sensory feedback in prostheses

Similar to the hand, artificial sensing can be divided into proprioception and tactile sensing.

Proprioception

Most of the principles and methods used in proprioception are much the same as those used for tactile sensing. These sensors are used to determine the relative joint angles to determine position and velocities or to detect the internal forces in the digits or the driving mechanism to determine contraction forces. The basic principles used for these sensors are:

- *binary contact switches* - detecting pre-defined joint angles through contact.
- *variable contact switches* - detecting various joint angles through contact.
- *geniometers* - detecting relative joints angles through bending.
- *strain gauges* - converting internal forces through deformation of digits.
- *stretch sensors* - determining forces in tendons.
- *potentiometers* - determining displacement or velocities.
- *current sensors* - detecting and controlling motor currents and torque.

Tactile sensing

Tactile sensors are divided into sensing different stimuli:

- *Simple contact:* detects the presence or absence of contact.
- *Contour:* converts the contact profile or contour of the object into a signal
- *Force:* produces information for grasping and manipulation control
- *Slip:* indicates relative movement between the sensor surface and the contacting stimulus.
- *Temperature:* detects the thermal conductivity and the absolute temperature of the object.

Sensor properties

The spatial resolution should be as small as possible for the available technology. The sensitivity and the dynamic range should be adjustable, stable, monotonic and repeatable. Hysteresis in the sensor is not desirable. The frequency response for the sensor is important and varies considerably with different types of force detection. The reason for the lack in sophisticated tactile sensing is due to the scarcity of robust, reliable, accurate and high resolution sensors. Certain requirements for tactile sensors were determined as a guideline for effective tactile sensing:

- The sensors' should be compliant and durable.
- The spatial resolution should be 1-2 mm.
- It should have between 50 and 200 sensing sites.
- It should be sensitive to detect a 0.05 N force.
- The sensor should be stable, repeatable and without hysteresis.
- The sensor's response must be monotonic.
- the time resolution must be at least 100 Hz.

Types of feedback sensors

Binary contact switches are the simplest way of detecting forces and touch. These sensors can not detect analogue forces but are limited to detecting specific force limits. The sensors consists of two metal plates which make contact when a specific force is reached. The sensor provides closed("on") signal when contact is made and a open("off") when there is no contact. The circuitry involved in the sensors are very simple, making it very popular to use in cases where analogue values are not necessary for sufficient control of the prosthesis.

Resistive sensors are mainly strain gauges which provide a simple and accurate way of measuring forces. The resistance of resistive sensors change when deformed. This change in resistance is measured and converted into strains which is converted into forces. The sensors provide a highly linear analogue signal making the conversion to forces very simple but effective.

Conductive sensors used are elastomers and silicone rubber. Conductive elastomers are commonly used to cover the tactile surfaces. Elastomers are compliant and their resistivity change with local deformations. Although these materials are hysteric and not very rugged the y provide a useful sensor for tactile sensing. Conductive silicone rubber are used as illustrated in Figure 3-40 for tactile sensing. The silicone deforms around separator contacts to make contact with an electrode base. An increase in pressure increases the contact area between the silicone and the copper, reducing its resistance. The resistance is measured and converted into a force.

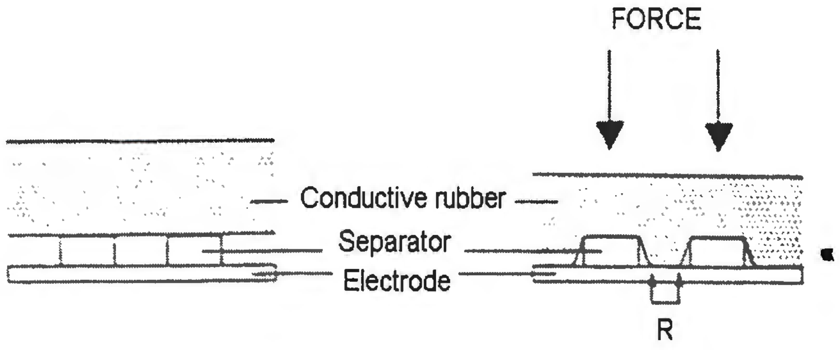


Figure 3-40: A schematic representation of conductive sensors

Piezoelectric materials produces an output voltage potential during dynamic deformation. *Pyroelectric materials* responds to heat fluxes by producing output voltages. The material PVF2 (polyvinylidene fluoride) are both piezo- and pyloelectric and has been used to detect force and temperature. Separating the output potential into two distinct signals representing the force and the temperature is quite problematic.

Capacitive sensors work on the principle that the capacitance of a dielectric material is a function of the thickness of the dielectric which changes during deformation or the contact area between the dielectric and the dielectric plates as shown in Figure 3-41. An increase in pressure will increase the contact area which will change the capacitance in the plates.

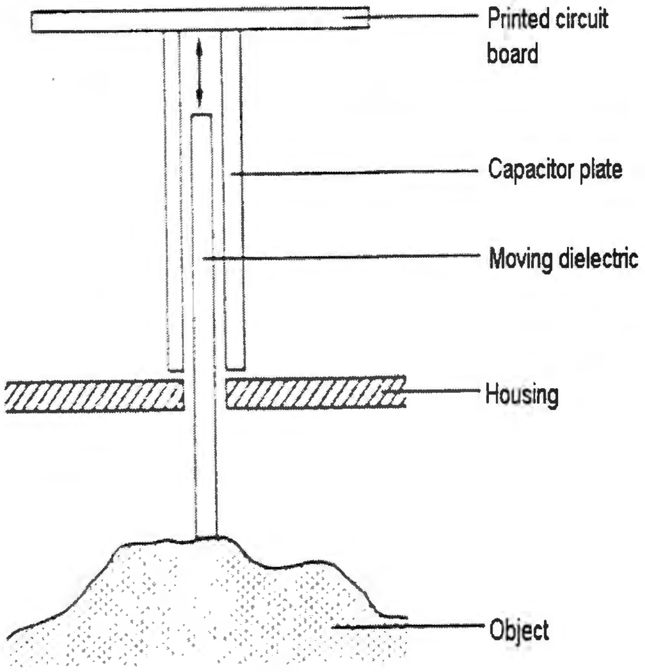


Figure 3-41: A schematic representation of a capacitive sensor.

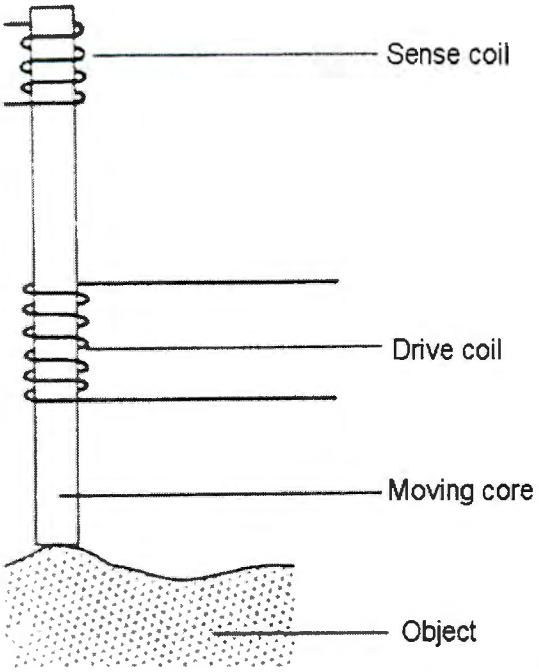


Figure 3-42: A magnetic sensor using coils.

Magnetic displacement either use the relative motion between electric fields or a magnetoresistive material. The method used in Figure 3-42 creates two electric fields by means of coils which undergoes relative motion during when a force is applied. A magnetoresistive material undergoes a change in electrical resistance when subjected to as magnetic field. In Figure 3-43 the magnetic field, caused by the electric wire, changes as the distance between the wire and the magnetoresistive element change.

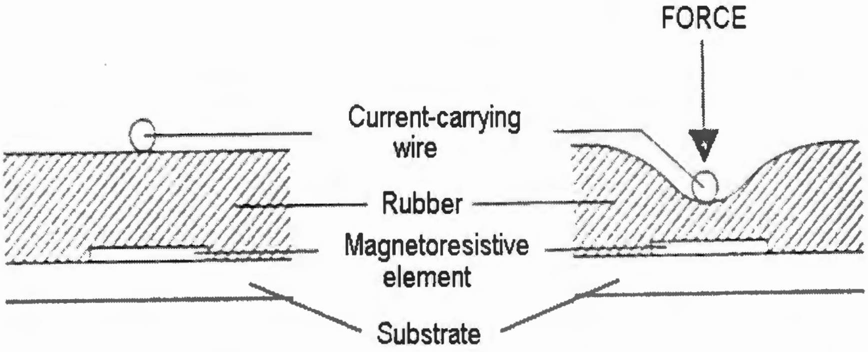


Figure 3-43: A sensor combining magnetic and elastic properties.

Magnetoelestic materials experience a change in their magnetic fields when subjected to stress. This change in magnetic fields can be converted into a signal.

Optical sensing is used in different ways for tactile sensing. One way is the shuttering of a light beam by contact deformation and another is the frustration of a total internal reflection. Another method, as show in Figure 3-44 is the detecting of light emitted by a LED (light emitting diode) and reflected from the object back to a photo-diode.[28]

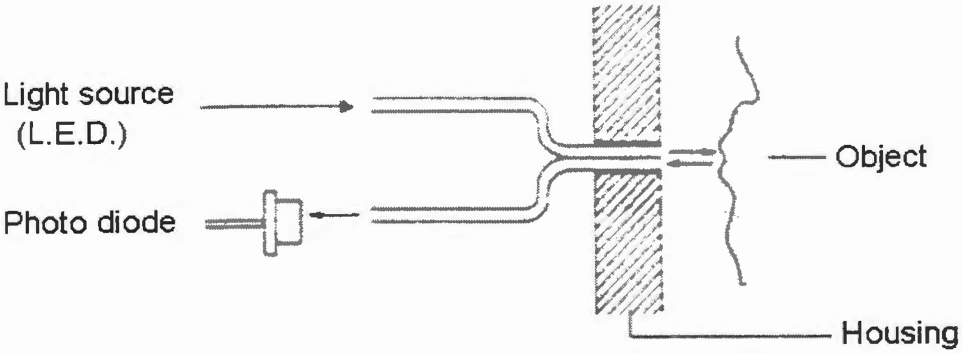


Figure 3-44: A schematic representation of an optic sensor.

To determine which sensors to use the modalities to be detected by the hand must be established and the advantages and disadvantages of the different sensors evaluated. The advantages and disadvantages of the various types of sensors are summarised in Table 3-3.

Sensors	**Advantages**	**Disadvantages**
Binary contact	Simple design Digital input	Fragile Limited use
Resistive	Wide dynamic range Simple construction Durability No hysteresis	Limited size Low spatial resolution.
Conductive	Wide dynamic range Durability Good overload tolerance Compatible with integrated circuitry Simple construction High spatial resolution Monotonic response	Hysteresis in some designs Large numbers of wires Often not linear Only normal force detected Low sensitivity Susceptible to noise Long time constants Low fatigue life.
Piezoelectric & Pyroelectric	Wide dynamic range Durability Good mechanical properties of piezo/pyroelectric materials Temperature as well as force sensing capability Stress components selectively sensed	Difficulty of separating piezoelectric from pyroelectric effects Inherently dynamic: output decays to zero for constant load Difficulty of scanning elements Good solutions are complex Lack of DC response
Capacitive	Wide dynamic range Linear response Robust High spatial resolution Good frequency response	Susceptible to noise Some dielectrics are temperature sensitive Limited spatial resolution
Magnetic	Wide dynamic range Large displacements possible Simple Stress component selectivity possible	Poor spatial resolution Mechanical problems when sensing on slopes Poor reliability Bulky

Table 3-3: Advantages and disadvantages of various tactile sensors.

Magnetoelestic	Wide dynamic range Low hysteresis Linear response Robust Normal force, shear, and torque capability	Susceptibility to stray fields and noise AC circuitry required Noise susceptibility Construction of dense arrays is difficult
Optical	Very high resolution Compatible with vision sensing technology No electrical interference problems Low cabling requirements	Some hysteresis Bulky Low spatial resolution Difficult calibration

Table 3-3: Advantages and disadvantages of various tactile sensors.

Vibration touch sensors are used to detect *slippage* between the finger surface and the object. A schematic presentation of the combined slip and force sensor is shown in Figure 3-45. Slip is detected by the microphone picking up the vibrational noise. To reduce the sensor's susceptibility to stray external signals it is imbedded within a chamber formed by a rubber tube. The tube runs to the finger surface and because the air in the tube exits next to the microphone it excites the microphone to react to the vibrations of the finger only. The acoustic characteristic of the microphone is far beyond that of the vibrations between the object and the finger but the vibration is being damped by the mass of the air in the tube.[21]

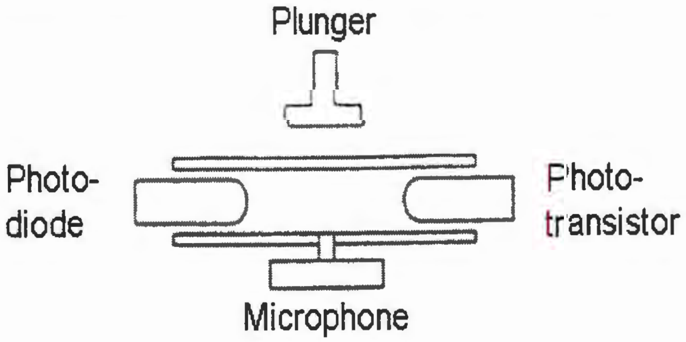


Figure 3-45: A combination between a vibrational and a light sensor.

The sensor developed for the SAMS control scheme detects contact force and vibration due to slip through the *Hall effect*. A schematic presentation of the sensor is given in Figure 3-46. It consists of a Hall effect detector covered by an elastomer, with a magnet on top and protected by a cover. The elastomer converts force into displacement which changes the magnetic fields and can be detected by the Hall effect sensor. The vibrations due to slip occurring are detected by the Hall effect sensors. The sensor is not susceptible to changes in temperature but to a small extent to mechanical vibrations and to quite a degree to external magnetic fields.[8, 22,28]

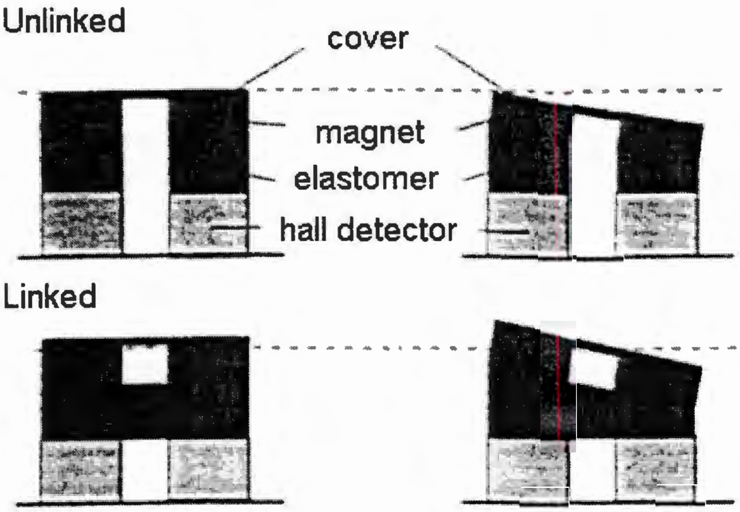


Figure 3-46: Schematic representation of a Hall effect sensor.

General comments on sensors

The problem in analysing the sliding phenomena is the determination of friction models and interaction between finger surfaces and the objects. Most finger-tips are made of compliant rubber-type material to increase the contact area. This complicates the force analysis for the contact interface beyond a single-point and line contact modalities and coulombic friction. Simplified models have been introduced obtaining limited conditions which prevent rolling and slipping under linear shear or torsional stresses. The challenge lies in detecting incipient slippage which is essentially what is needed to ensure stable grasp.

The improvement of prostheses depends highly on major breakthroughs in artificial tactile sensing technology and biological interfaces. The usefulness of current devices are limited by the strict cosmetic requirements and high functional demands imposed on them. A great problem is the transfer of the synthetic tactile information from the device to the neural system of the human body. Presently, localised force sensors, limiting force-switches and low resolution tactile sensors are being used but not very effectively. The use of tactile sensors will only be worth reconsidering when great improvement in the development of nerve guidance channels and neural connectors is achieved.[5]

Tactile sensors are still in the early stages and has thus far not contributed much to real applications in factory systems. More attention should be focused on quick useful analysis of dynamic tactile data involving the interaction between the object and the grasping device and less emphasis on shape recognition and visualisation which are not practical for use in normal limb prostheses. Properties like fingertip-pressure, slip and shear detection have more practical use for improving the functionality of prehensors.

Another problem with prostheses is the lack in control channels available to the user. The normal trend is to have single degree of freedom hands and have various hands for different functions. This is not ideal for feedback systems because it differs from the human hand it is replacing.

3.5.4 Tactile feedback

A few promising features for obtaining and using a signal from a single nerve for prostheses control do exist but none are currently commercially feasible. Until the technology allows the feedback information from the prosthesis to be connected directly to the neurons of the residual limb real progress in feedback systems is improbable. The amount of data that needs to be fed back to the amputees is too much and too complicated to be achieved practically in any other way. In the normal human all the senses are combined by the brain to interpret the final feedback while if substituted with any other system it is done by one or two of the senses leading to the limitations. If it is possible to develop a useful way to provide feedback to the user the space in the hand is so limited that is virtually impossible to incorporate in the hand itself which means additional components must be used. Any additional components tends to be in the way of the user in daily activities.[3]

The various *feedback* systems that have been tried are;

- mechanical vibrators
- electrical shock on skin
- auditory signals nerve stimulation in the stump (direct percutaneous wires protected from bacterial contamination by the use of a vitreous carbon button and transcutaneuosly by means of a implanted induction-powered radio receiver.)[14]

3.5.5 Future trends in feedback systems

The *University of New Brunswick (UNB)* developed an electrotactile display representing the pinch force in the thumb. *Duke University* are attempting nerve stimulation using telemetry to transmit the signal for the pinch force. The bio-compatibility of materials are the main drawback of his development. An Australian company, *Shannon,* utilises vibrotactile skin stimulation to represent pinch force detected by stain gauges in the hand. The *University of Utah* is developing a mechanism which pushes an object against the skin proportional to the pinch force. This is called extended physiologic taction (EPT). Clippinger et al. is experimenting with EMG electrode implants which are connected to receivers inside the body. An antenna on the outside of the body receives the signals from the receivers and send it to the control circuitry for the hand. This method ensures that there is no penetration of the skin by any part of the control system making the prosthesis less susceptible to infection.[3]

3.6 *Power supply of prosthetic hands*

The actuation power of prostheses can be divided into external power and body power. Body power has been used for quite some time and is still used more often especially in lower developed country but it seems to slowly be replaced by external power due to development in technology.

3.6.1 Body Power

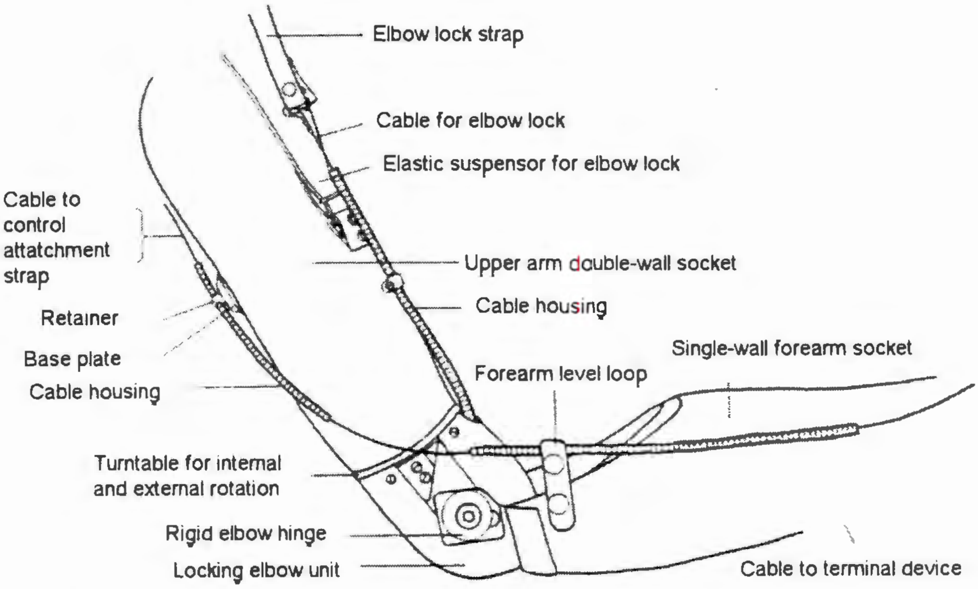


Figure 3-47: Standard configuration for a body powered prosthesis.

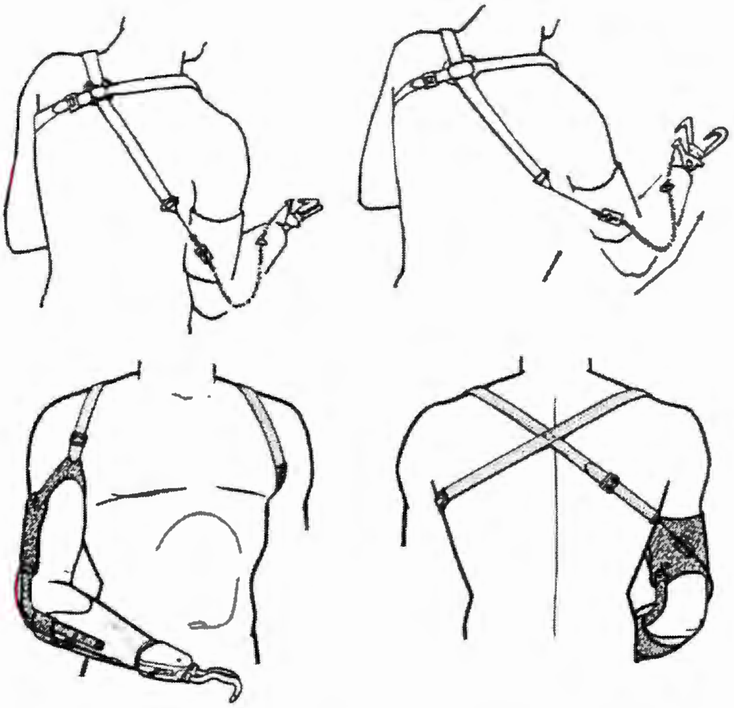


Figure 3-48: Standard method of shoulder control for the body powered prosthesis.

As the name states body powered prosthesis use the power of convenient residual body parts to actuate the prosthesis. Figure 3-47 shows the conventional body powered prosthesis and how it is actuated. The commercial prosthesis utilises the flexion of the residual amputated limb and the forward shoulder motion of the non-amputated side as shown in Figure 3-48. This power is used to open or close the terminal for below-elbow amputees and additionally to flex the elbow of the above-elbow amputee. For the latter the elbow is unlocked by a pull-switch and the elbow positioned by the power applied to the cable and then locked into that position. The power is now applied only to the terminal device. Most devices use the body's power to open the hand and then elastic bands to close the hand and grip the object.[23]

Another method of utilising body power is *Cineplasty.* This is a surgical method where a muscle, usually the amputated muscle, is either directly connected to the cable powering the prosthesis or it is connected to a servo system which supplies power to the hand proportional to the power applied by the muscle. In this method a skin lined tunnel is created in the muscle in which a peg can be inserted and then be connected to the prosthesis. The advantage of cineplasty is the direct, or in the servo system, proportional feedback to the user. The problem is crossing from an internal to an external environment the skin interface must be penetrated without the limb being infected.[3]

3.6.2 External Power

Externally powered prosthesis uses any practical form of actuation except that of the body to actuate the prosthesis. This means the prosthesis must incorporate the actuators, the energy supply for the actuators and the control circuitry, all of which should preferably be situated in the prosthesis itself. Although the latter two can be carried somewhere else on the body to conserve weight and space in the prosthesis but this could be quite cumbersome to the user. Previously, development in externally powered prostheses was hampered by the lack of portable energy sources leading to systems that were more promising than practical.

3.6.2.1 Electric power

The most practical and therefore most common form of electrical power currently in use are electrical motors. Electrical motors continue to improve with the latest being brushless DC motors with permanent samarium magnets, using ironless rotors and cellwound systems. These motors are smaller, lighter, have a higher electromechanical efficiency and power-to-weight ratio than their predecessors. The reason for using DC motors in the design is the ease of interfacing with the micro-controller and its reliable operation. The theory of developing electric motors or gear trains is not that complex but the actual implementation on such a small scale is problematic. Power used is supplied by 12V batteries but improved technology lead to 6V Nickel-cadmium batteries providing enough energy to power the system. The these batteries are very popular mainly because of their use in other common portable devices. These batteries need to have a short recharge time for it has to be fully recharged over night while not in use to supply the amputee with the optimum battery life during the day. The development in transmission systems is in the direction of eveloid gears and harmonic drives because of its high torque-to-weight ratio and helical gears for noise reduction.

Advantages:

- Electric motors and rechargeable batteries are very small, light, durable have a high efficiency and integrate well with electronic control systems.
- The compact controller leads to a smaller and more functional design which is easy to operate and to attach to the body.
- Circuitry for the control of the hand can also be supplied by the same batteries.
- Batteries have a high energy to weight ratio
- Batteries are rechargeable

Disadvantages:

- Systems have a slow *response time*.
- Hands have a slow operating *speed.*
- The battery packs are heavy and are located distally in the prostheses resulting in a large moment.
- Transmission systems and electric circuits are very sensitive to water and sand leading to low durability.
- The size of the motors restrict the number of actuators being used.[3,14,20,23,25]

3.6.2.2 Pneumatic power

The pneumatic power is normally supplied by disposable CO_2 gas containers activating pistons which actuate the prosthesis. The release of the gas is controlled by electric transducers.

Advantages:

- The light gas and absence of transmission systems makes the system up to 97% lighter than electric systems.
- The hands are very reliable and robust.
- The mechanisms are fast and quiet.
- The systems have a rapid response time.
- The mechanisms are mechanically compliant and thus more physiological.
- The actuators do not require locking mechanisms because constant forces are generated without energy expenditure.

Disadvantages:

- The system is cumbersome due to the additional canister of compressed gas carried with it.
- The power supply has a low *energy-to-weight* ratio.

A recent development Delft University of Technology have the following features:

- Small *disposable carbon dioxide containers* are commercially available. The canisters contain 7 g of CO_2 and has a mass of 32 g.
- A small *pressure-reducing* valve was developed to obtain the suitable pressure for the prosthesis. The valve has a mass of 28 g is 20 mm in diameter and 35 mm long.
- The small *electric-to-pneumatic converter* was built. The device uses the amplified myoelectric signal of 5 mJ at 3 V, with a 10 ms time constant, to activate the pneumatic pulse.
- A *Power Saving Concept* was introduced which divides the gripping cycle in a prehension and a pinching phase. During the prehension phase the hand opens and closes but as soon as contact with the object or thumb is made it switches to the pinching phase. A locking mechanism is introduced to resist reaction forces. This development reduces the gas consumption considerably.[30]

3.6.2.3 Others forms of external power

Electrohydrualic systems uses electrical energy to operate hydraulic pumps to power the hand. These systems are hampered by the fact that the components are not standard components used in other common applications and the systems seems to have leakage problems. *Mechanohydraulic* systems transfer mechanical cable motion in hydraulic motion to actuate the hand. *Thermopneumatic* systems are being considered but no feasible attempt has been made in this area.[24,25]

3.6.3 Body Power vs. External Power

The main difference between body power and external power that with body powered prosthesis the prosthesis is powered remaining muscles of the body is utilised to actuate the joints and terminal device. In externally powered prosthesis power from and external source is used for actuation. The difference between the two forms of actuation leads to a significant difference in the design of the two systems. A not so obvious but very important difference between body powered and externally powered prostheses are the socket attachments to the body. With the body powered prostheses harnessing is necessary to provide stability and power to the prosthesis. In the latest socket designs the socket slips onto the stump using bony prominences of the joints as attachments. This makes it unnecessary to use harnessing for below-elbow prostheses. Commercial designs for hands used for both applications are much the same since it only consists of one degree of freedom. The driving mechanism in the body powered hand is attached to a cable leading to the muscles where in the externally powered hand it is connected to a actuator and normally a gear train in the hand itself, changing the design slightly to fit the actuator inside the hand.[14]

The advantages of body powered hands are their relatively light mass, robustness, easy maintenance and low cost. Sensory feedback to the user are through vision mainly and the arm prosthesis interface. Body powered prostheses consist of feedback through the skin socket contact as well as the through the harness. The latter is absent in externally powered devices leading to a lack of extended proprioception (EP), depriving the user of any natural feel for the force applied to the object. Body powered prostheses are uncomfortable, wear out clothing, cause clothing to appear lumpy and their functional value decreases with more degrees of freedom. Space and weight is quite a problem with externally powered prostheses since the actuator as well as the power source and the control system must be fitted into the prostheses. The muscles used to control body powered prostheses are not the same used to control the hand naturally leading to control difficulty. Externally powered hands have relatively slow speed, low attractiveness and the higher mental demand on the user (60% higher) but has a higher pinching force and opening size.[3,23,25]

3.6.4 Robotic hands

It is becoming clear that robotic systems need to have capabilities similar to that of the human hand to perform effective grasping tasks. Various robotic hands have been developed for use in the industry. These hands differ from prosthetic hands in the sense that they only substitute the functions of the hand and not the hand itself. This place far less restrictions on the size and together with more funding available in normal industry these hands are more elaborate in their designs and control systems. With the latest, and hopefully future, progress in technology these hands or their principles could be applied in the design of prosthetic hands.

3.6.4.1 Designs

The *Belgrade/USC* incorporates four motors; one for each finger pair and two controlling the thumb. The hand has no adduction/abduction and has a selfadaptability feature, which, after a contact pad on one of the fingers is touches the object, allows the other fingers to keep on closing until pressure in all fingers are equal. The hand only provide grasping of objects but no manipulation The hand is being developed into a prosthetic hand driven by two dc motors. The hand is equipped with 16 touch sensors and has five types of grasp:

- *cylindrical:* to grasp a cylindrical abject.
- *spherical:* to grasp a sphere.
- *lateral:* grasp between the thumb and the side of the index finger.
- *power:* grasp between thumb and opposing fingers.
- *precision:* grasp between the tip of the thumb and the index finger.[9,38]

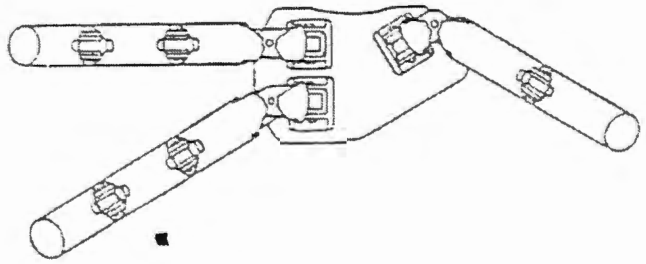


Figure 3-49: The Okada manipulator.

Okada has developed a three fingered 11-degree-of-freedom hand for industrial object handling. Two fingers have four degrees of freedom and the thumb three degrees of freedom as shown in Figure 3-49. The finger are actuated by cables running through coil-like hoses to prevent interference. To provide good grip each finger tip is stuffed with a small rubber ball. The hand is programmable to perform certain complex tasks. Algorithms were developed to determine the position of joints to achieve the optimal gripping shape for the hand by determining the optimal operational direction for the fingers, expressed by an axial line peculiar to the object.[8,9]

The hand developed by *Lian et al.* (1983) has four fingers, with three joints each(Figure 3-50). The most proximal joint has two degrees of freedom; adduction-abduction over a range of 30° and flexion/extension of 120°. The remaining joints can only flex and extend with a range of approximately 90°. The thumb is more complicated with the proximal joint also having two degrees of freedom. The adduction/abduction has a range of 90° around a axis skewed from the plane defined by the fingers. The flexion/extension motion has a range of slightly less then 90° rotating within a plane defined by the palm. The next joint has a flexion/extension range of 60° and the distal joint a range of 90°. The fingers are equipped with hemispherical friction tips and are powered remotely through stainless steel cables. To achieve effective grip of an object the hand shape must maximise the contact area. The manipulator is developed to produce five important human grasps:

- *Tip opposition* - between the tip of the index finger and the tip of the thumb.
- *Lateral opposition* - between the side of the index finger and the tip of the thumb.
- *Palmar prehension* - with the fingers and thumb wrapped around a cylinder.
- *Spherical prehension* - with the fingers and thumb wrapped around a sphere.
- *Digitopalmar opposition* - when the fingers and the palm form a opposition pair.[9]

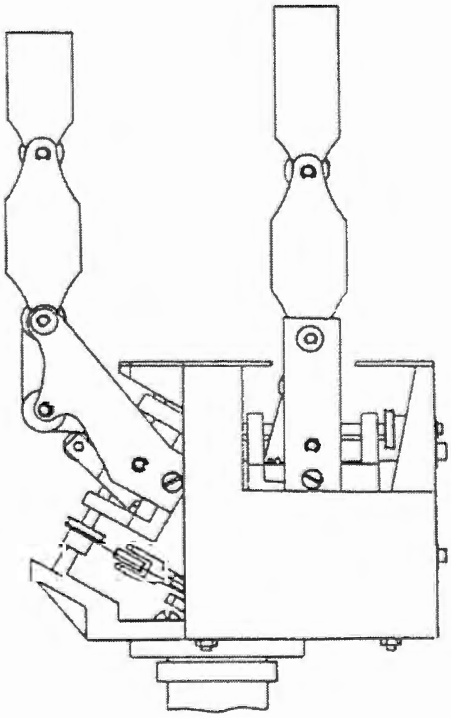


Figure 3-50: The Lian manipulator.

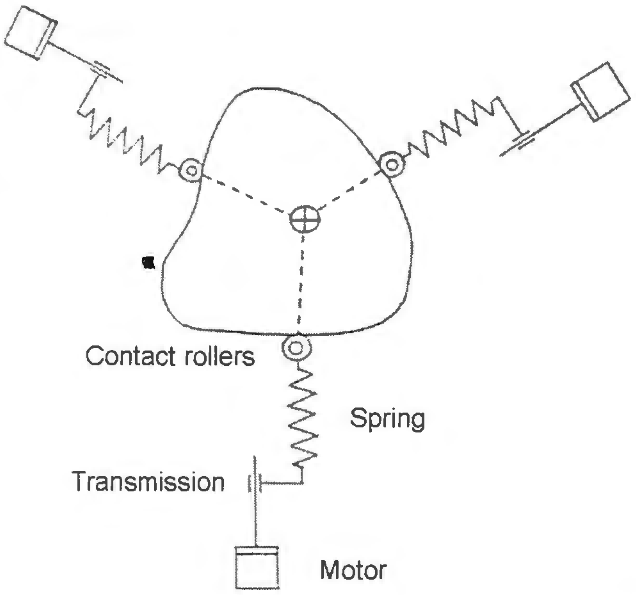


Figure 3-51: A schematc presentation of the principle for the Hanafusa manipulator.

The *Hanafusa et al.* manipulator is a non-anthropomorphic gripping device working on a concept of grasp stability. The device is a planar three-fingered hand implementing an analytical grasping algorithm. Each finger has one degree of freedom and is arranged 120 degrees from the adjacent fingers as shown in Figure 3-51. The fingers are each actuated by a step motor through a coil spring. The force inside the coil spring and the tip displacement of each finger is measured by potentiometers. The contact point of the fingers are on rollers to eliminate all tangential force components. A potential function consisting of the sum for all the fingers, of the product of the finger force and the differential movement integrated over its path from the initial state, is obtained. This potential function is minimised to obtain the stable finger positions. The system requires a vision system capable of determining the objects silhouette limiting its practical use.[8]

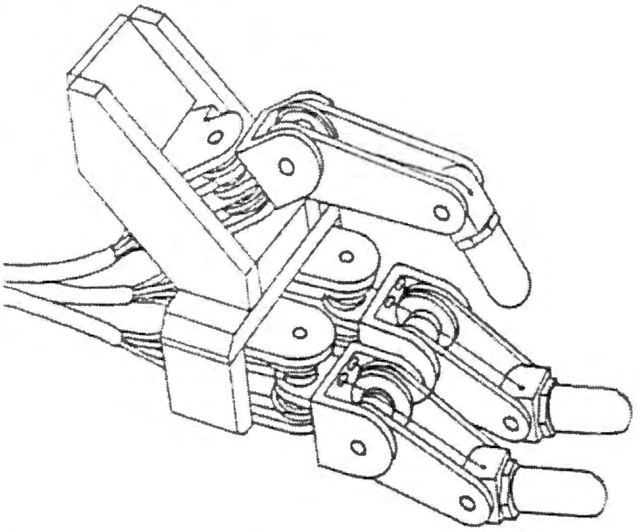


Figure 3-52: The stanford/JPL hand.

The *Stanford/JPL* hand is an anthropomorphically driven hand. The hand has three fingers, with three links per finger, and three-degree-of-freedom contact is achieved by point contacts with friction or planar contact without friction. As shown in Figure 3-52, the hand is actuated by a tendon scheme using cable with tension sensors. The three joints of each finger are driven by four antagonistic Teflon coated tendons. Each finger has two parallel axis joints to provide the flexion/extension motion and a proximal joint providing adduction/abduction. Each joint is flexed independently but extended by a common actuator. The fingers are remotely driven by 12 motors, four actuators per finger to provide it with torque control for each joint. The fingers have hemispherical, force transducing fingertips. Problems with the hand includes the complex control system to control all the actuators and the difficulty in maintaining calibration of the hand.[8,22]

The *Utah /MIT* dextrous hand is one of the most truly anthropomorphic hands available. The hand consists of three four-degree-of-freedom fingers and a four-degree-of-freedom thumb. The lengths of the phalanx and the positions of the joints are not the same as the human hand to accommodate the tendons running through them. Different from most other hands the design of the hand was with the intention of modelling a human hand but still it lack a few properties like palmar opposition and the thumb was positioned exactly opposite the other three fingers and are all the same size. The hand is powered by extremely fast remote pneumatic cylinders, with low friction and high power, through polymeric tendons. The 16-degree-of-freedom hand, as shown in Figure 3-53 is actuated antagonistically by 32 independent tendons and actuators which make each joint's stiffness controllable. The hand is faster than the human hand and delivers the equivalent forces. The hand is equipped with two reflex motions; proximal stiffening and distal curling. The joints of the hand are fitted with position sensors and tendon force sensors for both flexion and extension tendons. The disadvantages of the hand are the complexity of control due to all the actuators and the adduction/abduction motion causes interference with the flexion/extension motion in the finger.[8,9,]

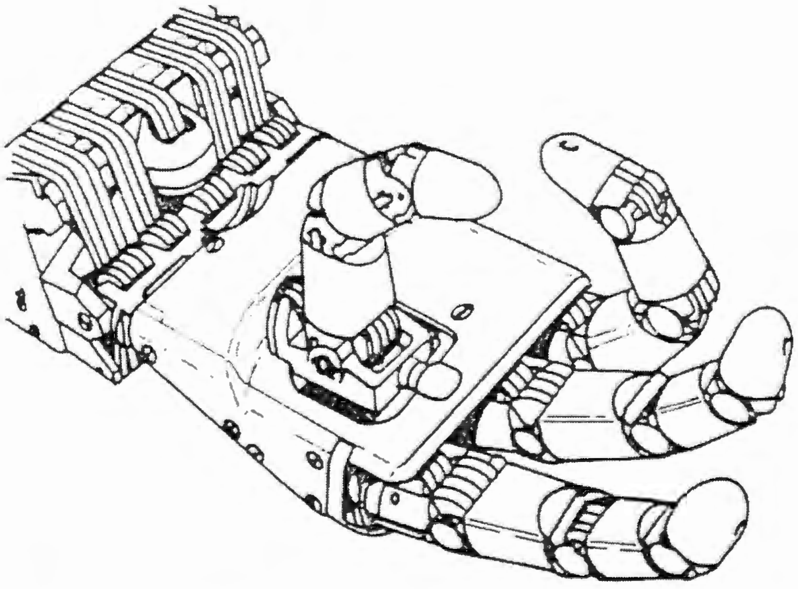


Figure 3-53: The Utah/MIT dextrous hand.

The design of the *Guo-hand is* based on the features of the Utah/MIT and Stanford/JPL hands. The design has three fingers and the actuators are stationed in the forearm. Characteristic configurations for the hand are:

- Each finger has flexion/extension as well as palmar joints.
- All cables for flexion/extension pass through the adduction/abduction joint.
- Each joint has an independent single degree of freedom.

The new design showed the following improvements over the existing hands:

- There is no interference between motions.
- The number of actuators are reduced.
- There is no decoupling of the tendon-drive system.

The numbers of actuators needed to drive the hand is equal to the number of degrees of freedom associated with the hand. The finger mechanism consists of a three-bar linkage system with three degrees of freedom. There are three rotary joints; two for flexion/extension and a proximal joint for adduction and abduction. Each finger is driven by three motors through four tension cables. The four cables are used for the flexion/extension of the joints and together with two additional cables for the adduction/abduction joint. Each joint uses a two-way tendon-operated actuation by a single motor. Potentiometers are attached to each joint to detect angular displacement and tachometers monitor the motor speed.[9]

Oomichi developed a robotic upper limb to be powered by the master-slave principle, with the user being used as the master to be mimed by the robot. Functions of the hand have been divided into:

- *holding* the object firmly and
- *manipulating* it inside and outside the hand

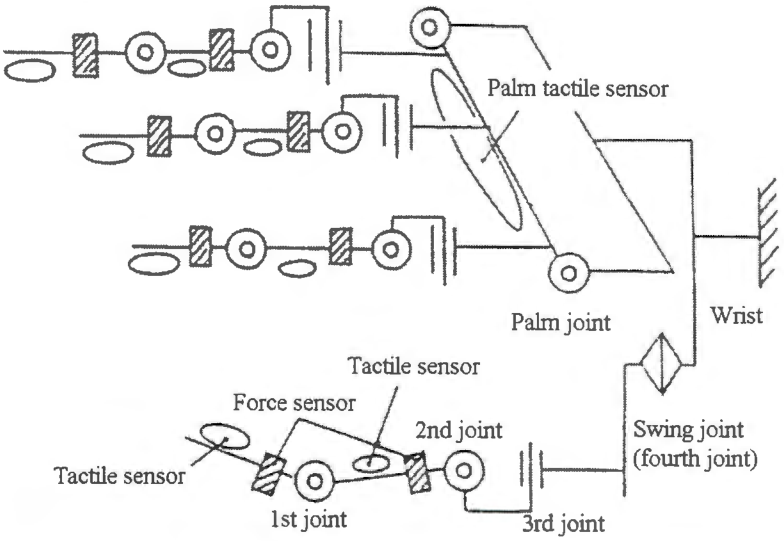


Figure 3-54: Schematic representation Oomichi hand.

The hand is designed to adapt to the shape of the object being gripped. The hand has four fingers with three degrees of freedom each and a fingertip shape similar to that of the human finger were chosen. The schematic design of the hand is shown in Figure 3-54. The finger has force and tactile sensors as shown in Figure 3-55. The texture of the tactile sensors are of great importance; it must have flexibility for stable holding , yet be hard enough to determine contact points.[29]

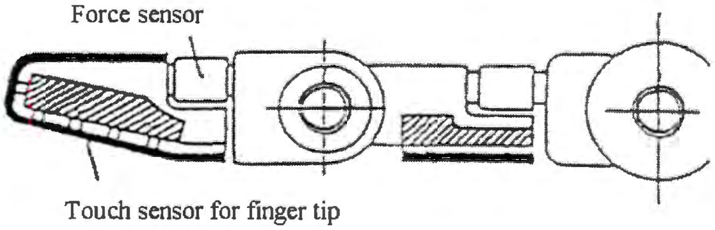


Figure 3-55: The design of the finger.

Hanford hand is a unique multi-fingered manipulator using hydraulic actuators. It consists of four fingers and an opposing thumb as shown in Figure 3-56. The system is adaptive to incorporate a form of feedback and to be applied as a prosthetic prehensor. Grip pressure in the hand is proportional to the internal fluid pressure. There are ten chambers to provide full articulation of which four are used for the four fingers, two for the thumb and four for the wrist. These chambers flex all the fingers with the

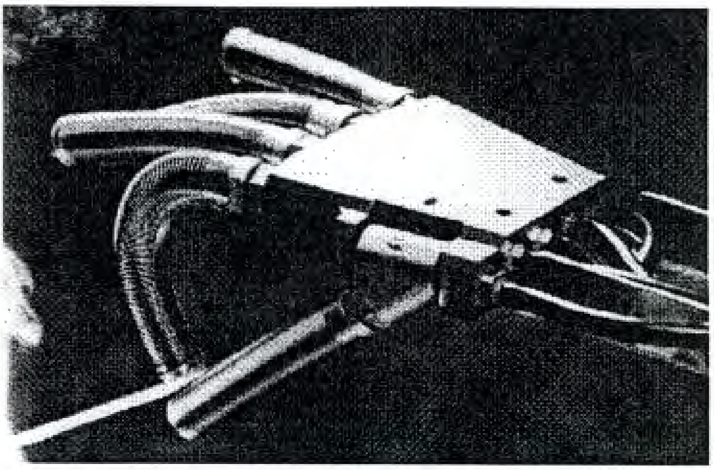


Figure 3-56: The Hanford hand.

additional chamber enabling the thumb to articulate at the side of the hand. The chambers are filled with liquid and have a baffle to separate the liquid from the pneumatic actuation supply. The fluid inside the fingers stiffens them in their curled grasping position. The system will be designed to use disposable or refillable CO_2 cartridges mounted on the body. Alternative methods are a bladder pump placed in the sole of the foot to charge with every step or a rechargeable desk-top compressor. The valves are situated at the base of each finger powered by a small rechargeable battery controlled by a microprocessor. The valves release air near the stump when used which has a advantageous cooling effect on the stump. Individual fingers are easily replaceable since it forms an simple independent unit. Each finger curl when the internal pressure in the individual finger rises. This is achieved by the Battell prehensile device shown in Figure 3-57. The fingers of the device are made of corrugated tube with circular bellows. A flat strip is connected to the palmar side of the finger to constrict extension on that side. Only an industrial prototype has been developed but the manufacturers claim that it could be developed into a prosthetic hand. Features of the hand includes:

- simplicity of design
- light mass
- cosmetic appeal
- durable[35]

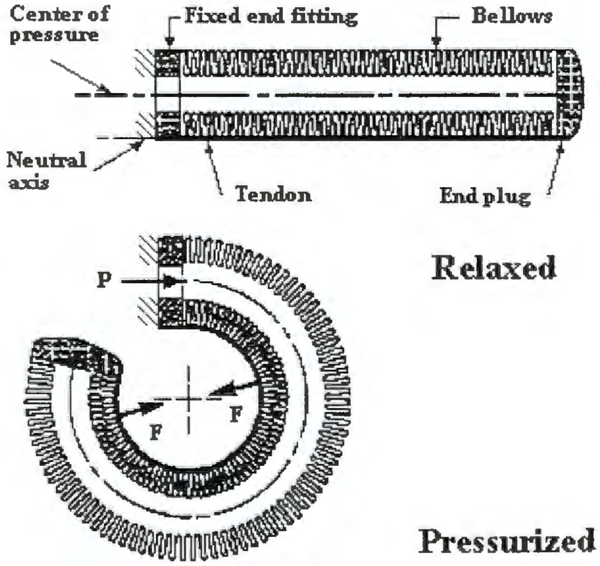


Figure 3-57: The Battel finger mechanism.

The *IRC-hand* is a multi-fingered dextrous grasping device with features including (Figure 3-58):

- 3 fingers with symmetric and asymmetric hand configuration
- bi-directional tendon drive and joint actuation
- 9 independent degrees of freedom controlled by 9 dc motors
- joint position sensors
- PC-based controller and servo amplifiers[16]

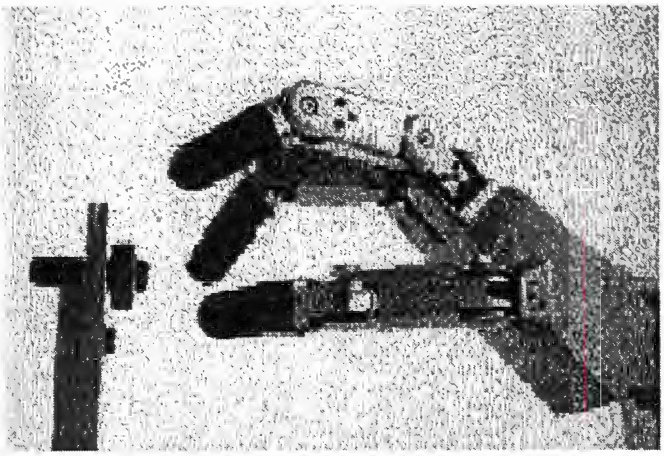


Figure 3-58: The IRC hand.

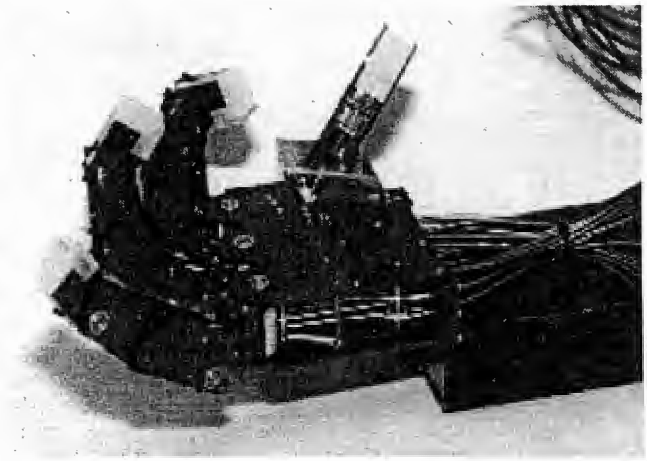


Figure 3-59: The Rice hand.

The *Rice hand*(Figure 3-59) consists of three fingers and an opposable thumb. It has 16 degrees of freedom of which 13 are independent and 3 dependent. Each finger has lateral motion and two independent knuckle motions with the third knuckle coupled to the second. The thumb has four degrees of freedom including two knuckles, a lateral joint and a large bending joint. The lateral joint is at an inclination of 30 degrees with the vertical. The hand is powered through tendons by 13 dc motors.[6]

3.6.4.2 Control systems

These multi-degree-of-freedom hands are often driven through numerous tendons. Various tendon drive mechanisms are being used of which the most important ones will be discussed. There three main configurations are; N, N+1 and 2N, where N represents the number of degrees of freedom and the classification is made by how many actuators are needed to drive the N degrees of freedom.

N - There are two ways of achieving N actuators. The first, as shown in Figure 3-60(a) requires pre-tensioning of the system to prevent slacking but produce high friction and backlash [Okada]. The second method is shown in Figure 3-60(b). This configuration prohibits low contractions when stiff springs are used, which are used for high extension force and rapid response time. It also leads to high energy dissipation required by the actuator to pull the spring.

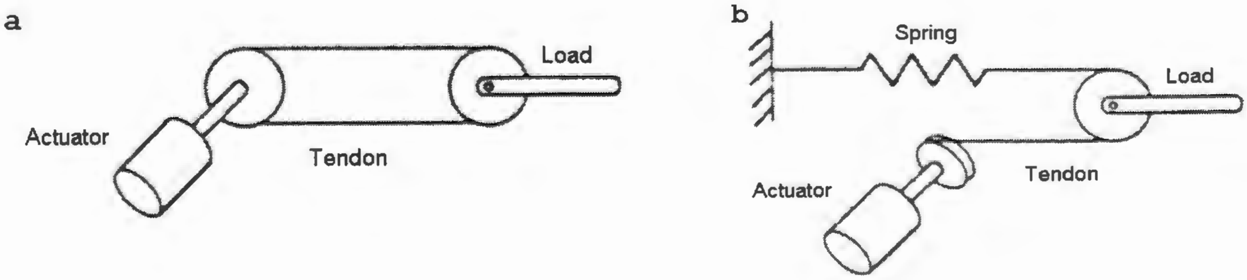


Figure 3-60: Two ways controlling N DOF using N actuators.

N+1 - Each joint is flexed independently but is extended by a common actuator [Stanford/JPL]. This method reduces the number of actuators from the 2N configuration. The disadvantage of the configuration is that one actuator must resist three other actuators requiring a much stronger actuator. for the extension than for the flexion.

2N - Two actuators are used to drive each joint, each pulling an opposing tendon in agonist/antagonist fashion. This system, as shown in Figure 3-61 increases the volume of the actuators but provide low co-contraction forces, independently controlled joints and equal-strength actuators and tendons [Utah/MIT].[17]

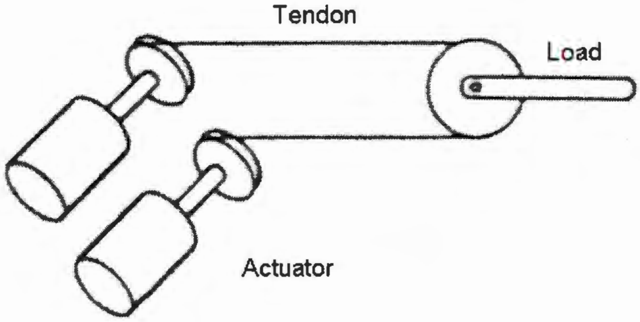


Figure 3-61: Achieving control over N DOF using 2N actuators.

Most of the existing manipulators are driven by remote actuators through tendons. With high performance operation high antagonistic forces and tendon slack can cause problems making the new algorithms necessary. Various algorithms are developed to optimise the complex control of these devices and reduce backlash, extended range of motion and wear compensation in these systems.

DEVELOPED MODEL

Chapter 4

4.1 Introduction

A concept model for a multi-fingered hand was developed. The model is built out of Lego and can be controlled through a personal computer. The software developed to interface with the computer is object orientated providing easy control of the hand by means of various windows and buttons. The user controls the hand using two basic signals in various sequences. These control signals are the input for the lower level control of the hand which is performed by the developed software. Pre-programmed hand shapes are selected by the user according to the shape of the object. The object is then gripped and released on the users command. The hand has five fingers with a total of five independent degrees of freedom. The thumb and index finger can flex independently while the middle, ring and little finger are control semi-independently by the same actuator. Additionally the hands allows rotation of the thumb to provide opposition and abduction/adduction of the fin fingers. The fingers are actuated by five motors located inside the palm of the hand. The fingers are flexed using tendons while other functions are achieved through gear mechanisms.

4.2 Initial decisions

There are currently many commercial prosthetic hands available. Most of these hands have only one degree of freedom. The development of single degree of freedom hands and especially body powered hands has stagnated, indicating that the optimum design for maximum functionality has been approached. Although very practical these hands have limited use compared to the human hand resulting in a need for multi-fingered hands. A few multi-fingered hands are under development but none is really successful because of the high demands imposed by the human hand. It is especially the combination of versatility, light mass, compactness and robustness that makes it extremely difficult to produce a multi-fingered hand that is practical and functional enough to be used successfully by amputees.

It should be clear that there is a definite need for a practical yet more functional multi-fingered hand. The latest development in technology has sparked a new interest in the development of such hands. This sparked the author's interest in the developing of a concept model for a multi-fingered prosthetic hand which would adhere to these requirements. The nature of the funding for this concept model implied that it should be used afterwards as an educational tool for school children to stimulate interest in the scientific fields.

Using Lego Dacta as a designing tool was a result the availability of it to the author and the possibilities provided by the medium. An advanced laboratory using Lego Dacta for design purposes has been established over the past years at the Department of Mechanical Engineering at the University of Cape Town. This laboratory has a large variation of parts already available including, basic structural components, computer software and interface components as well as actuators and sensors.

4.3 Design Methodology

The project undertaken by the author was of a very practical nature and since the model developed was only a concept model using Lego the design methodology followed was of an empirical nature. The literature study done by the author forms a very important part of the design methodology since this background was used to form and evaluate principles for the design of the hand. Using Lego as a design tool is ideal for this method because a mechanism concept can easily be built. The concept can then be tested and evaluated, and if necessary, adjusted to test a different concept. The nature of the model and strict space restrictions placed on the hand makes it absolutely necessary to find the optimal design and not just something that works. This makes it a very long and tedious process of redesigning mechanisms to reach perfection. The actual forces in the structures will never exceed that of the members due to the low energy output of the actuators making a in depth structural analysis of the members unnecessary. The other important factor is that the design of the final prosthetic hand will inevitably depend on components that are commercially available which might differ considerably from that used by Lego. This leads to a higher emphasis being laid on the principles of the design rather than actual dimensions and strengths. Since existing designs do not seem to be very successful the author tried to make use of original principles keeping previous designs and methods in mind and using them as reference for comparison and evaluation.

4.4 Actual design of the hand

4.4.1 Initial decisions

Prosthetic hands consist of definite parts which are standard to most designs. As stated by Bowker et al.[3] hands are developed as an independent component that is screwed directly onto the shaft of the prosthetic arm or if a wrist connector is used it screws onto the wrist connector. The model designed therefore also had to be an independent component replacing the normal hand, excluding the wrist.

For the scale of the hand it was decided to keep it as close as possible to full scale, keeping the dimensions of the Lego members in mind. This meant that some of the Lego components had to be altered and glued into position because the standard Lego, if only pressed together, would be too big. The alternative was to develop the hand at a larger scale and not adjust any of the Lego members. This was decided against because the strength of the actuators will not be sufficient to drive the hand at such a scale. Furthermore the model would be too impractical to transport and use effectively further use as educational tool. Finally and most importantly the greatest challenge in designing a prosthetic hand is the space restrictions, in other words to work with what is available and to fit that into the hand. Building a hand at double the scale would defeat this purpose entirely.

4.4.2 Actuator choice

A very important decision to be made was the choice of actuators to drive the hand. Lego Dacta has two forms of actuation available; pneumatic pistons and electric motors. The pneumatic piston's biggest advantage is its size. The pneumatic pistons(Figure 4-1(a)) are considerably smaller than the electric motors with an advantageous cylindrical shape to fit longitudinally into the hand, thus being physiologically compatible.[30] The disadvantage of this system is, it can only be manually controlled by levers(Figure 4-1(c)) and must be manually pumped up by the pneumatic pump cylinder(Figure 4-1(b)). It is also possible for the piston to be pumped up by a compressor system consisting of an electric motor and a pneumatic piston which would defeat the purpose of using pneumatics. Alternatively non-Lego components consisting of a gas canister and pneumatic control switches could be used to control the pneumatics but using the standard Lego interface box with its available software functions would pose problems with proper force control of the pneumatics. The 9V electric motors(Figure 4-2) were chosen because of the convenient control through the available Lego software. The force applied by these motors are easily controlled by controlling the running potential of the motor. In existing prosthetic hands electric motors are used in most designs due to its compatible electric circuitry, the commercial availability of components and its small power supplies.[3,14,25]

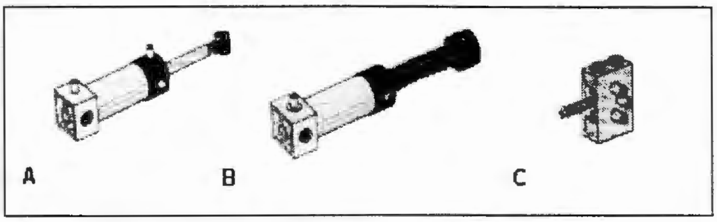


Figure 4-1: Pneumatic components.

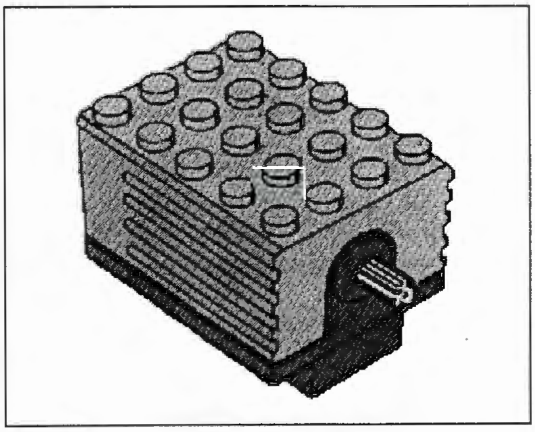


Figure 4-2: Electric motor(9V).

4.4.3 Control choice

Lego Dacta components can be controlled with a personal computer. The CTRLab package provides customised software for the control of standard components. This software is very convenient for lower level designing but is limited to standard Lego components and not as strong as other control software packages since it was originally designed for educational purposes and not for advanced designing. Lego developed standard subroutines for use in other software packages. These subroutines control most of the important functions of the Lego components using the Lego interface box. The Lego interface box (Figure 4-3) is a serial, bi-directional computer interface card which with built in timers using software commands to communicate with Lego components. The interface box has 8 outputs and 8 inputs available to the Lego components. The 8 input ports of the Lego interface box were not enough for effective control of the hand because the hand has too many sensors that has to be monitored. Since it is not possible to use two Lego interface boxes at the same time the author was forced to use an additional digital input/output computer interface card to handle the additional digital inputs to the hand. The card used was the PC-14 dual 8255 input/output card with 48 programmable lines. Communicating to this card and the Lego interface box can be done simultaneously. Hence the UCT control box(Figure 4-4) was developed consisting of the necessary circuitry for the control of the hand.

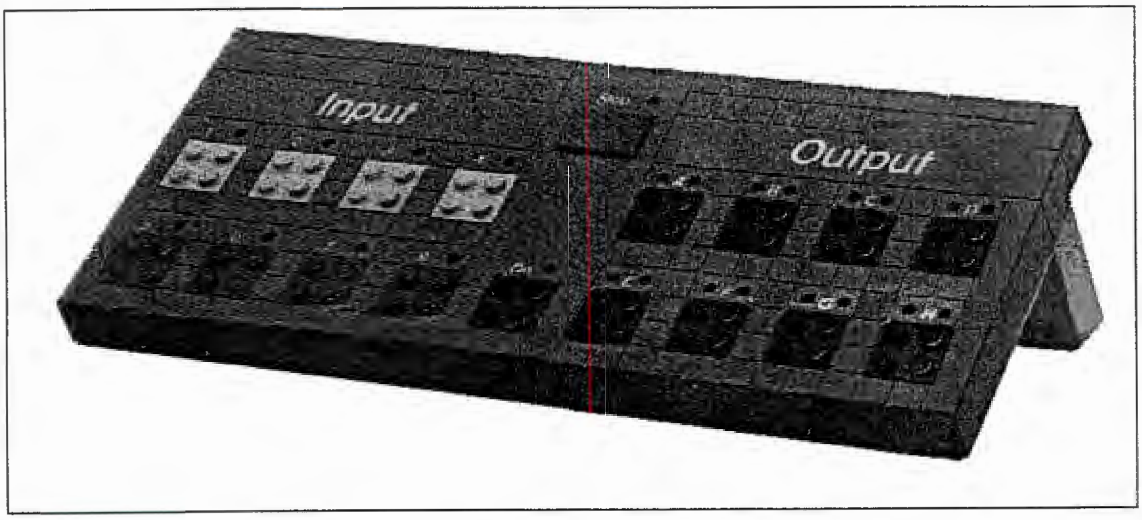


Figure 4-3: The Lego Interface box.

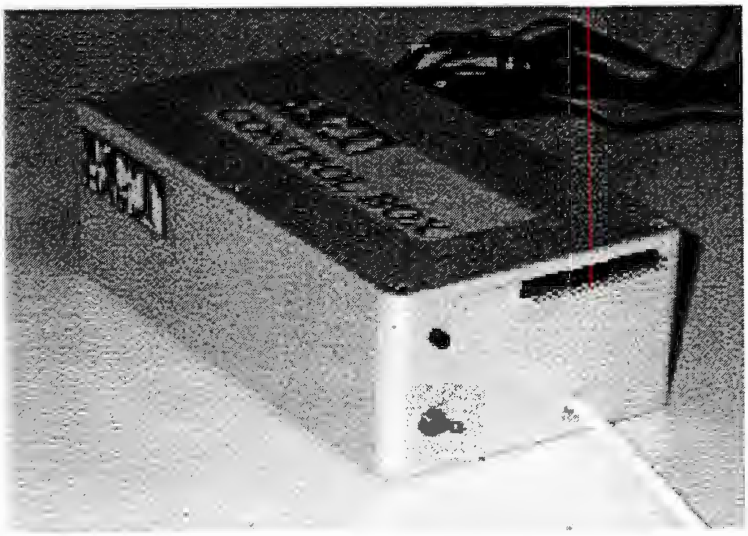


Figure 4-4: The UCT control box.

The author decided to use Visual Basic as programming language since it is one of the software packages supported by the Lego subroutines to communicate with the Lego components. Visual Basic can also be used to communicate with the PC-14 card. The author's previous knowledge of programming in Basic languages as well was availability of Visual Basic also contributed to its use. Visual Basic is a user friendly Windows object orientated program, making the final product ideal and easy to use by children. The final program guides the user through information windows while operating the hand making the program easy to use.

Various methods of interesting control for the hand were considered by the author. Using a virtual reality glove would have been interesting but is impractical since gloves are expensive and the hand is designed for prosthetic use for which the control differs considerably from virtual control. Prosthetic hands use a limited number of control signals while virtual hands use multiple signals. Another consideration was using electromyographic signals from the users muscles to control the hand the same way it is used in a real prosthetic application. This would have made the use of the hand more interesting but unfortunately the equipment is very expensive and could not be obtained on a permanent basis. Alternatively it was decided to use the Visual Basic objects in a similar way to control the hand. The control buttons were used to represent the electromyographic signals from the muscle and are used in an analogue fashion to the muscle contractions of the prosthetic user. To replace this control system can easily be done by having any alternative signal representing these buttons and would only need minor adjustments to the main program.

The hand is developed for two purposes; serving as a concept model for a prosthetic hand and to be used be children as a educational tool. For the latter an easy control method with many individual controls for components are ideal while for the prosthesis a more complicated control scheme, using less input signals, is essential. The author therefore decided to develop the interface program to incorporate both these strategies. In the program the user can choose which of these two control schemes are to be used.

4.5 Motor selection

The choice of motors and location in the hand is crucial to the rest of the design and is therefore one of the first and most determining decisions to be made. Due to the space restriction on the design, only 5 electric motors could be fitted into the hand. All the motors fit into the palm of the hand as shown in Figure 4-5.and form the

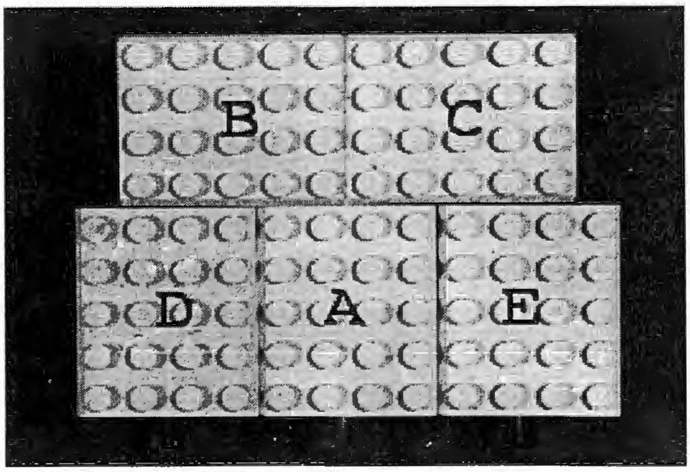


Figure 4-5: Positioning of the motors in the palm.

basic structure of the hand with all the other components attached to them. The motors are arranged to duplicate the shape of the human palm while providing a stable structure and have the driving shafts easily available for actuation. The functional distribution of the motors are very important and depend highly on the functions to be achieved by the members of the hand, which in turn depend on the functional grasping shapes which are to be achieved by the hand. Various studies have been done on the functions of the hand determining the most important grasping hand shapes used in ordinary everyday life. These functions differ from one user to another depending highly on their occupation. The results of these studies differ as to which specific hand shapes are essential for effective prosthetic use but there is a definite consensus that shapes can be divided into two classical groups;[4,20,23,41]

- *Precision grips*: between the tips of thumb, index and sometimes middle finger.
- *Power grips*: between all the fingers and the thumb together with the palm of the hand.

The author combined the results from all these studies to determine which functions of the hand are the most important in the process to assign the functions of the different members of the hand and therefore determining the motor functions. Firstly it was determined that for proper grip it was neccessary for all the fingers to be flexed and extended. Only one motor can be assigned to achieve both these functions for the individual fingers. There are not enough motors to assign one to each finger so they had to be distributed to the most functional fingers to ensure the highest functionality and grip force. The thumb and the index finger were each given one motor since studies of the human hand show that these two fingers form the most essential part of most grips. In the human hand (Figure 2-2 and Figure 2-3*)* it can be seen, in contrast with the other fingers, the two fingers consist of separate muscles to give them independent control. It is also a trend in most developing prosthetic hands and existing dextrous robotic hands to have more control over these two fingers than the others. Of the remaining three fingers the middle finger performs the most important function since it forms the center of the power grips with the other two providing stability to the grip and additional gripping area and strength. In most functions performed by the hand these fingers are very closely coupled to perform a combined movement. In many designs the last two fingers are only dummy fingers and are not powered to form part of the grip. Kinoshita et al.[19] show that during the average grip the index finger carries about 43% of the total grip force, the middle finger 26%, the ring finger 18% and the little finger about 13%. This shows the combined contribution of the ring and little finger accumulate to 31% of the total grip. This was considered to be substantial enough to justify having these two fingers actively actuated. The lack of more available motors meant these two fingers could not be actuated individually, therefore compelling the author to develop a mechanism actuating the last three fingers semi-independently with one motor. Most research shows that it is essential for the thumb to have an additional degree of freedom to achieve the opposition function performed by the thumb of the human hand.[8,9,22,29,38] A separate motor is therefore used to rotate the thumb along an axis longitudinal to the palm. The last motor is used to abduct/adduct all four fingers which is essential to ensure a proper grip on large or spherical objects. This widens the gripping area and enables the fingers to grip more towards the side of a spherical object providing better grip. The abduction/adduction of the fingers are dependant on each other with their speed and direction of angular deflexion being unique to each finger. The final distribution of the motor function are as follows:

- *Motor A:* Flexion of the thumb
- *Motor B:* Flexion of index finger
- *Motor C:* Flexion of last three fingers
- *Motor D:* Rotation of thumb
- *Motor E:* Abduction/adduction of last four fingers

The locations of the motors are assigned according to the accessibility for the motor to the function it is performing. Flexing of the fingers were considered to be the most important function of the motors, receiving preferential treatment to the other functions. Motors were therefore assigned to the flexion functions first. Motor B was assigned to the index finger because of its location on the index side of the hand and the fact that it would be easier to actuate the thumb from one of the motors at the back of the hand. Motor C was assigned to the flexion of the three fingers also because of the location on the front of the of the hand providing good accessibility to the fingers. Motors A and D were assigned to the flexion and the rotation of the thumb. The final distribution of these functions to these motors was determined later by the mechanisms incorporated in the final design. The only motor left was Motor E and was therefore assigned to the abduction of the fingers. The numbering of the motors are assigned according to the connection to the Lego interface box and not to the position in the hand to make the development of the control less confusing (Figure 4-5).

4.6 Finger Design

4.6.1 Basic finger components

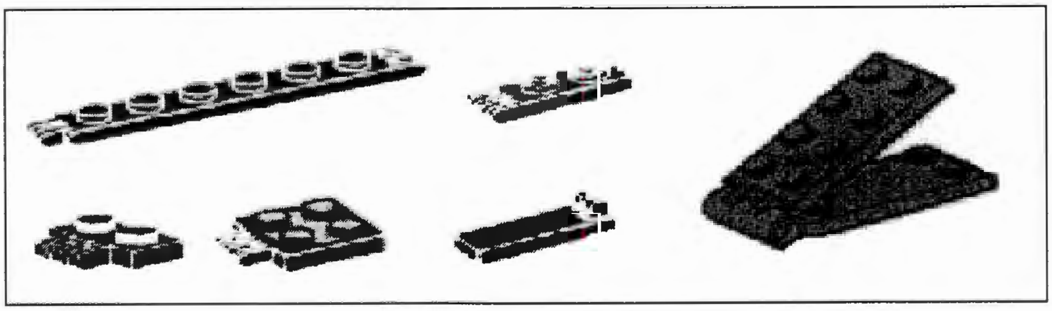


Figure 4-6: Frictional joints.

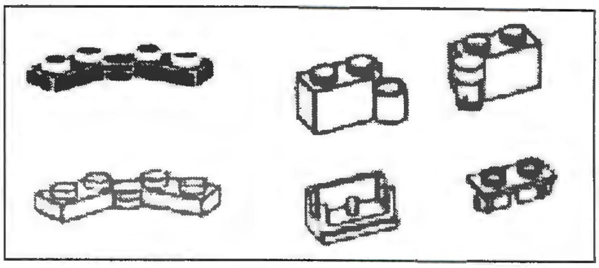


Figure 4-9: Non-frictional joints.

The design of the finger was based on the actual human finger. It consists of three members connected to each other by two IP(interphalangeal) joints and connected to the palm of the hand by a MP(metacarpophalangeal) joint. All the joints are allowed one dimensional flexion/extension in the longitudinal plane of the hand. The MP joint has an additional degree of freedom in the adduction/abduction movement of the finger. The first step in the design of the finger was the choice of joints and connecting members. Of the joints available(Figure 4-6) some of the ideally shaped ones were friction joints and could therefore not be considered for use in the model. Some of the other joints available(Figure 4-9) are functionally ideal to the purpose but the axis in which the members attach onto the joint is perpendicular to the preferred longitudinal axis. Using various combinations of different Lego Dacta parts very useful joints can be constructed(Figure 4-7). The bottom-right joint shown in Figure 4-7 was chosen by the author as the most functional joint and was used for the design of the single degree of freedom joints for the hand. It was chosen because of the compact size, low friction, fairly high tolerances, symmetric geometry and the possibility of adding additional features to the joints. The MP of the hand is a two-degree-of-freedom joint which is more problematic to construct. Two two-degree-of-freedom joints are manufactured by Lego(Figure 4-8). These joints are very functional but the control of two degrees of freedom in one joint is very problematic and the advantages gained by incorporating it do not justify the resulting complications. A configuration consisting of two separate joints was therefore constructed to represent the

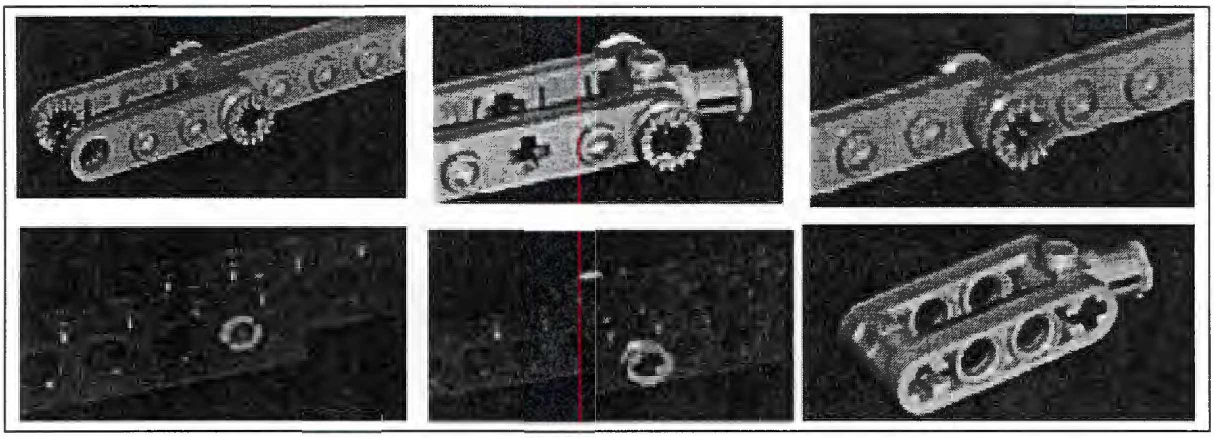


Figure 4-7: Constructed joints.

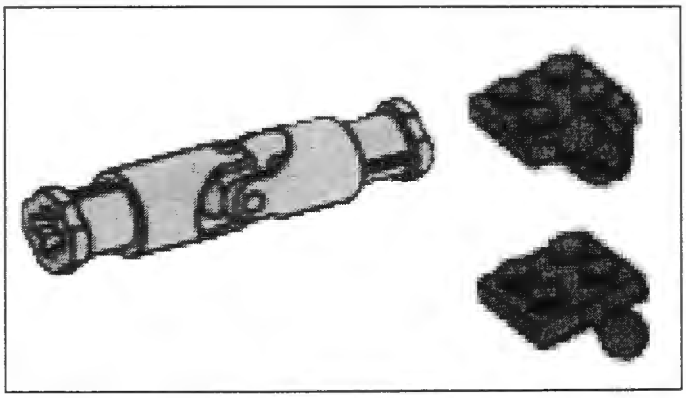


Figure 4-8: Two-degree-of-freedom joints.

MP(Figure 4-10). The joint is easy to make, strong, functional and above all easy to control. The shaft fits with a close high friction fit into the two side panels forming the 'female' part of the joint. The shaft fits comfortably with a very low friction but high tolerance into the central 'male' member of the joint. These joint configurations can easily be taken apart if changes or reparations to the hand need to be made.

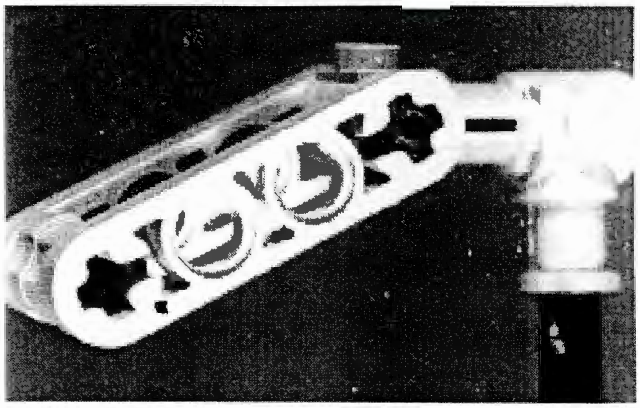


Figure 4-10: The two-degree of freedom MP joint.

4.6.2 Finger trajectory

The actual design of the finger mechanism is crucial to the functionality of the hand. It determines the grasping trajectory and the final grip on the object. The trajectory is very important to provide a cosmetic appearance during hand closure while an effective grip on the object is the most important function of the hand. The challenge in the design of the finger mechanism lies in the achievements of both; a good closing trajectory and a stable grasp on most objects.

4.6.2.1 Design

In robotics there are enough actuators to control most joints individually making it a control problem rather than a mechanism problem. In prosthetic hands though, there is at most one actuator to control the whole finger motion turning it into a mechanism design problem. Most previous designs incorporate either a solid finger or a linkage finger mechanism, both having a fixed closing trajectory.[3,,10,39] The solid finger is easy to make but does not have a cosmetic closing trajectory and only provides good grip on certain objects. For the designs of the linkage mechanisms the closing trajectories and the dimensions of the finger members are normally determined by some optimisation process. The optimal path is found by optimising the minimum energy expenditure and member forces, the best cosmetic trajectory and the maximum efficiency for the system subjected to various constraints. These configurations provide a good grip and grasping trajectory as long as the object being gripped is of regular size and shape because the finger is not able to change its actual shape when an irregular or especially smaller object is gripped. The human hand has various mechanisms ensuring that any size or shape object gripped by the hand are gripped with the maximum stability.[3,7,11] A very important factor for a stable grip is to achieve the maximum contact surface. The finger can change its geometry to adapt to the object's shape by 'curling' around the object increasing the contact surface. This is a complex effect to achieve in a finger using only one actuator and the author could only find two attempts at achieving this in previous hands. The mechanism used by Crowder[4] incorporates force bar differential systems to distribute moments equally along the MP and proximal IP joint. This principle is very promising but unfortunately consists of various small and flat interconnecting linkages making it impractical for use with Lego members. Another way of achieving this is not really practical for this work but worth mentioning, is the mechanism used in the Hanford Hand[35]. In this design the hydraulic pressure inside a corrugated finger is used to provide the grasping force while a stiff tendon on the inside of the finger ensures the curl of the finger around the object. This mechanism should provide a fairly adaptable grip and good force distribution but the use of hydraulics invalidated it as a practical option.

The author decided to use the principle employed by the human hand to achieve this adaptable grasping motion since it is has proven itself to be the best gasping tool ever. The first decision was to use tendons to actuate the finger instead of gears and linkages. Tendons combine high strength with flexibility making them ideal for actuating an adaptable finger. Tendons are also able to change the direction of the applied force and makes it easy to direct a force in a specific direction by using guides. The most important thing to keep in mind while using tendons is that they apply one directional forces only which means that there should always be another form of actuation to reverse the action of the tendon.

The first design considered was using two tendons; one for flexion and the other for extension (Figure 4-11(a)). Both tendons were connected to the base of the distal phalanx. The extensor tendon ran down the back of the finger in guides across the joints and was connected to a elastic band mounted at the base of the finger. This acted as a passive extensor of all the joints at all times. The flexor tendon ran down the inside of the finger through guides directing the forces to flex each of the joints. This design did not have individual control over joints making it impossible to achieve a specific closing trajectory for the finger. From this another mechanism was developed incorporating an additional extensor tendon(Figure 4-11(b)). This tendon was attached to the base of the middle phalanx and ran down the same

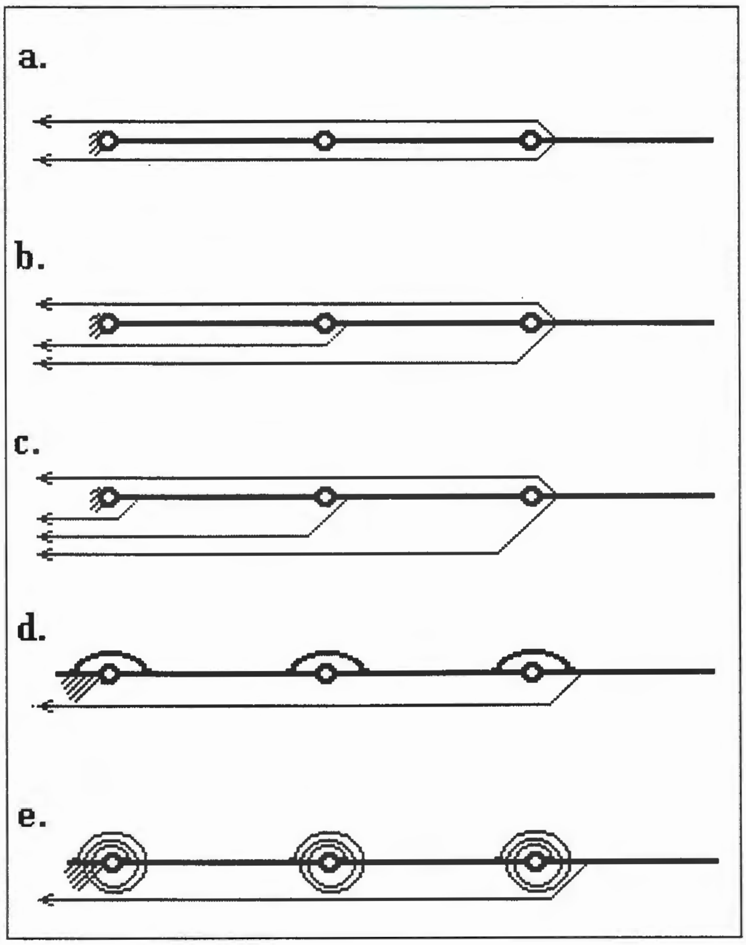


Figure 4-11: The various designs to find optimal finger closing trajectory.

guides as the previous tendon and was connected to the base of the finger via a separate elastic band. This provides individual control over both joints. By determining the size and length of elastic bands the desired optimal closing trajectory for the finger could be achieved with the finger still being able to alter its trajectory when an object is grasped. By attaching a elastic band to each joint(Figure 4-11(c)) would provide control over each joint. The problem with this mechanism was the elastic bands were very space consuming because they were fitted on the proximal end of the tendon. There was also some interference between the tendons running in the same guides. Incorporating the elastic bands in series with the tendon inside the finger between guides was considered but there was not sufficient space between the guides to allow enough deformation of the bands without touching the guides. The next option was to apply the elastic bands at joints(Figure 4-11(d)) instead of through tendons. This would provide individual control over each joint. This design was a step in the right direction but the deformation of the elastic bands around the back of the joints led to non-linear and frictional deformation of the bands which produced unpredictable results. To overcome this problem the elastic band at each joint was replaced with a torsional spring(Figure 4-11(e)). Torsional springs provide a linear relationship between the relative angular deflection between members and the resistance moment in the joint providing an easy way of analysing the system and determining the desired trajectory. These torsional springs were easy to incorporate in the design of the joint as shown in Figure 4-12. The torsional springs are useful for conducting electrical current across a joint without additional moment resistance to the joint due to the absence of wires crossing the joint.

Figure 4-12: Cross section through a joint showing the rotational spring.

4.6.2.2 Determining motor torque

The trajectory of the finger is dependant on the stiffness supplied by the spring in each joint and the positions of the guides. Therefore the correct spring constants and guide positions have to be determined to ensure a cosmetic closing trajectory for the finger. At the same time the design of these variables must be optimised to ensure that the motors have enough power to fully close the fingers while the springs are strong enough to ensure proper closure of the limit switch when fully opened, ensuring sufficient contact for conduction of the current. The torque supplied by the motors is not very large compared to the forces needed to make proper contact in the limit switches and at the same be able to fully close the fingers. The author decided use an analytical model to determine these variables and optimising it to obtain the final finger configuration. This would be less time consuming and give a more structured approach to determining the effect of the variables on the trajectory than using a trial and error method. Before an analytical model could be determined the electric motors had to be tested to determine the maximum torque which it can deliver. This was performed to ensure the motors will have enough power to close the fingers properly and not to determine the actual gripping forces. From the beginning of the project is was clear that the motors would not be strong enough to justify a strength analysis but that the design of a functional mechanism is of primary importance.

Using the Lego gears is the best way to step down the output speed of the motors is through a worm gear combination(Figure 4-13). Using worm gears are favourable for actuating prosthetic hands because they provide a natural back-lock mechanism which conserves a lot of energy while gripping objects[3]. The smallest gear, the 8 tooth gear, was chosen from the available Lego to be driven by the worm gear to conserve space. The gear ratio for this combination is 32:1 which was not sufficient so it had to be stepped down twice as shown in Figure 4-14, increasing the gear ratio to 64:1.

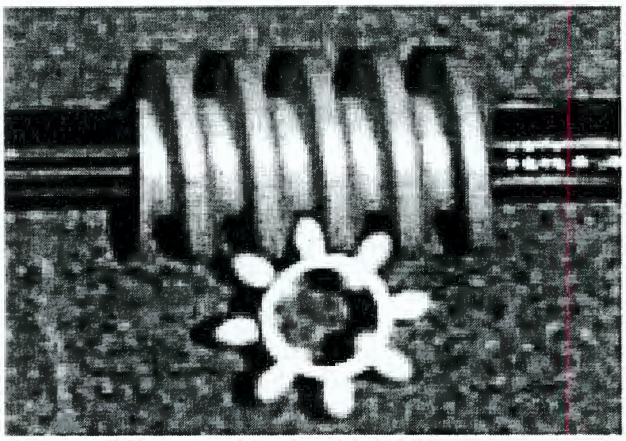


Figure 4-13: The worm gearbox configuration(32:1).

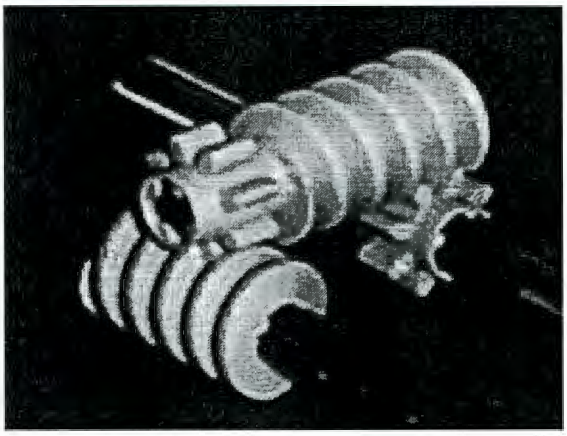


Figure 4-14: The double worm gearbox configuration(64:1).

To determine the design of the fingers the output of the motors had to be determined as described in Appendix A. The torque at the output shaft of the motor was measured to obtain a value for the actual torque for the motor. The torque versus speed curve for this test is represented in Figure 4-15. The motor was connected to the 64:1 gear box and the torque versus speed curve shown in Figure 4-16 was determined as in described in Appendix A.

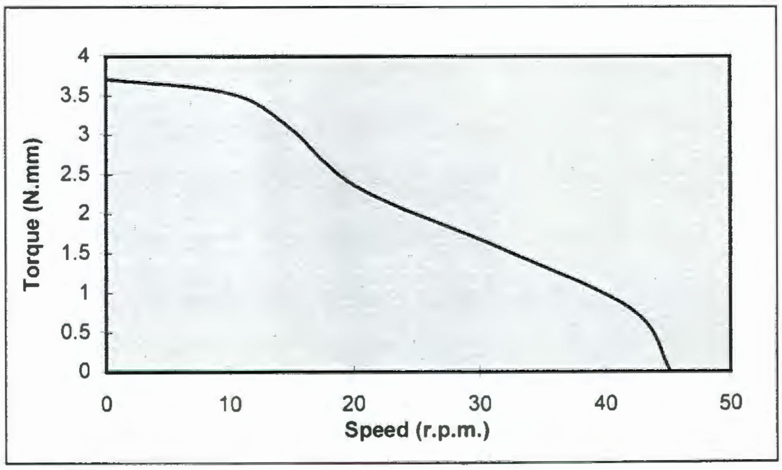


Figure 4-15: The torque vs. speed curve measured at the motor output shaft.

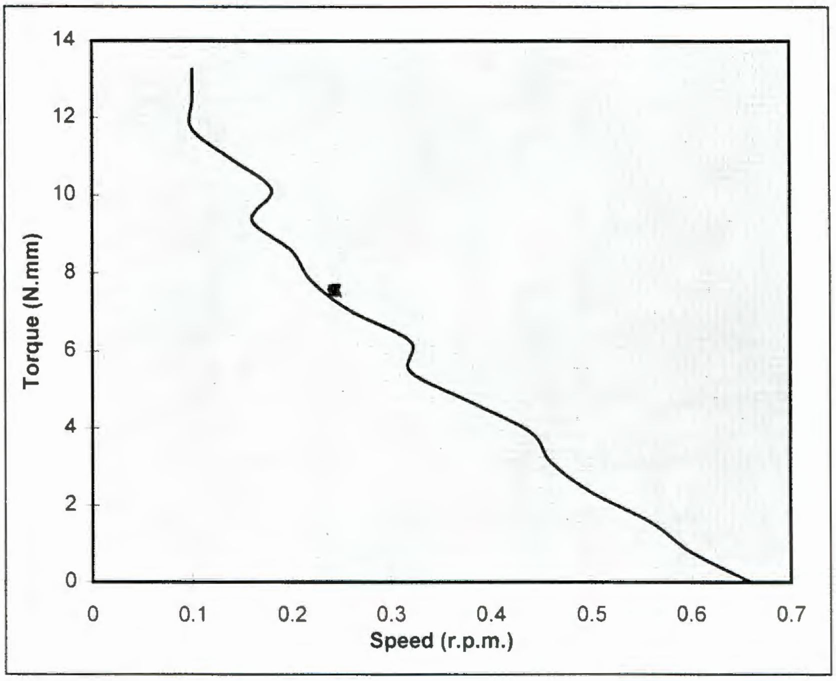


Figure 4-16: The torque vs. speed curve measured at the gearbox output shaft.

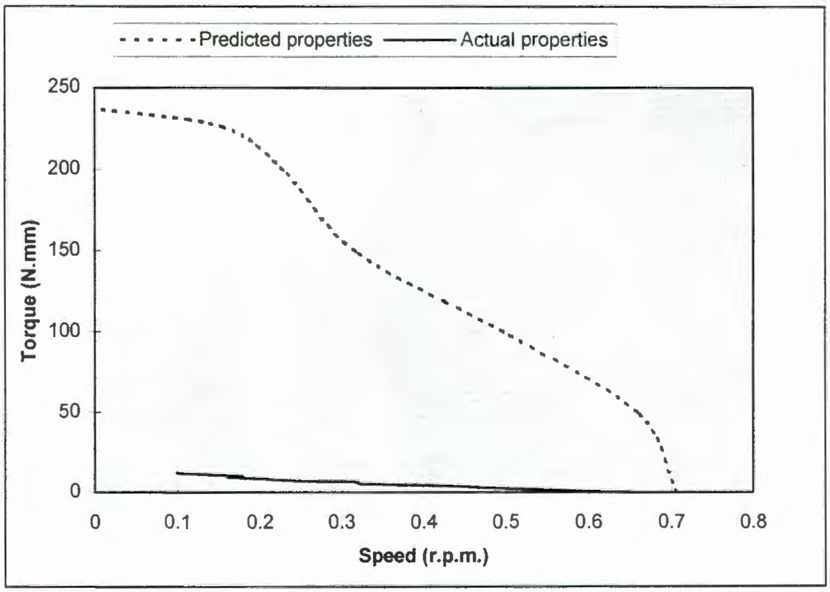


Figure 4-17: Comparing the measured torque versus speed curve with the theoretical curve at the gearbox output shaft.

The torque and speed measured at the output shaft of the motor were converted according to the gear ratio as presented in Appendix A to be able to compare the outputs and thus determining the efficiency of the whole system. The theoretical output for the system is much higher than the actual torque measure at the gear output shaft for the same speed (Figure 4-17). The maximum torque for the motor was found to be 3.7 N·mm with the theoretical torque at the output shaft of a gearbox being 237.32 N·mm. The actual measured maximum output torque at the gear box output was measured to be 13.258 N·mm which gives an efficiency of 5.6 % (Appendix A). This meant that the losses in the system are very high and that the effect of the system on the output torque is so great that it was not necessary to determine the torque curves for all the motors. Using the measured maximum torque at the output of the gear box and applying it to the finger through a tendon winding onto a pulley with a 4 mm diameter the force available to the finger was determined to be 1.05 N (Appendix A). For the remaining tests and calculations for the fingers the pulling force at the finger tendon were estimated to be a maximum of 1 N.

4.6.2.3 Analytical model

Figure 4-18 shows a schematic representation of the finger mechanism to be analysed with the angles and the various dimensions of the members. The aim of the model was to change the different variables in the mechanism and determine the effect of these variables on the finger trajectory. The most important variables under investigation are the position of the tendon guides, the spring constants and the initial spring deflections at the various joints. A force is applied at the tendon in different force steps and a static analysis of the system is performed for each force step to determine the finger position for that force. As the force increases the finger will close until it reaches maximum closure for a specific force. This force must be smaller than the maximum force that can be supplied to the finger by the actuators. Using the finger positions at different force steps a finger trajectory can be established for the specific finger configuration. The static position of this three degree of freedom system is determined by using parts of *Castigliano's Theorem* for determining the deflection from strain energy. This can be summarised as; the total energy input to a system is equal to the total deformation energy of that system where the latter can be integrated over the whole system as a function of the resultant moment at each point in the system.[36] In the model of the finger the deformation of the finger members can be assumed to be negligible compared to that of the torsional springs. This means that the energy equations can be written as a summation of the energy at each joint instead of an integral over the whole finger. A free-body diagram (Figure 4-19) is drawn for each joint and the resultant moment at that point determined for the applied force as a function of all the variables. The derivation of these equations is presented in Appendix A.

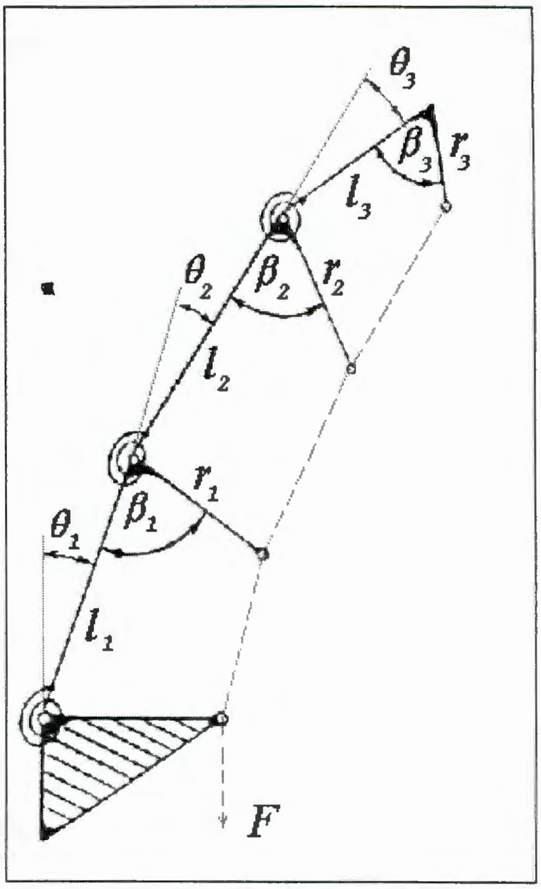


Figure 4-18: Schematic representation of the finger with modelled parameters.

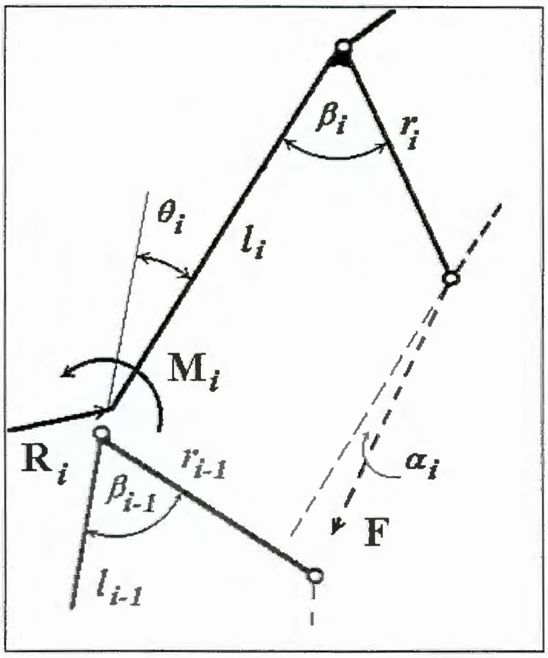


Figure 4-19: Free body diagram of each member of the finger.

Moment balance at each joint yields:

$$M_i = f(F, \theta_i, \beta_i, \beta_{i-1}, r_i, r_{i-1})$$

$$= F\{\cos\alpha_i (r_{i+1} \sin\beta_{i+1}) + \sin\alpha_i (l_i - r_{i+1}\cos\beta_{i+1})\}$$

with:

$$\alpha_i = \arctan\left[\frac{r_i \sin(\beta_{i-1} + \theta_i) - r_{i+1}\sin(\beta_i)}{l_i + r_{i+1}\cos(\beta_{i-1} - \theta_i) - r_{i+1}\cos(\beta_i)}\right]$$

The sum of the energy as a result of the moment at all the joints is equal to the deformation energy of the whole system.

Total deformation energy:

$$U_{Tot} = \sum_{i=1}^{3} \tfrac{1}{2} K_i \theta_i^2$$

The easiest way to solve for the angular deflections is to optimise this energy equation. For an applied force the system will reach an equilibrium at the lowest energy consumption. The energy equation is therefore minimised using optimisation software to find the equilibrium state for each applied force. Restrictions and boundary conditions are imposed on the system. The boundary conditions are the maximum and minimum relative deflections for each joint. The minimum deflexion is reached at full extension when all the relative angles are zero and the maximum deflection at full flexion where the angles are determined by the position of the flexion stops in each joint. The natural restrictions on the system are that the moment at each joint is equal to the moments in torsional springs due to relative deflection between adjacent members.

Natural restriction in each spring:

$$M_i = K_i \theta_i$$

Boundary conditions for each joint:

$$0 \leq \theta_i \leq \theta_i^{\max}$$

Optimising this analytical model for the minimum deformation energy using the relative angles as variables produce the relative angles for the system for any applied force. By changing the value of the force applied the trajectory for the specific finger configuration is determined. Since the optimisation program (Eureka) can only handle a limited number of variables in the form of symbols, software was developed to convert the numerical values of the variables for each trial into standard input deck (Appendix B). Additional software were developed to read the output deck of the optimisation program and produce stick figures of the finger for each test which represent the closing trajectory for the finger (Appendix B). These stick figures for the different configurations were compared to determining the effect of the variables on the closing trajectory and eventually to find the optimal closing trajectory.

A basic finger(Figure 4-20) was constructed to use as basis for all the tests. The finger was constructed using the scaled dimensions(1:1.2) of the human finger while the guides for the tendons were placed in the most convenient locations where it could be practically fastened with efficient stability. The consequence of the convenient placing of the guides is that the construction of the individual members of the finger are not identical. This meant that the free body diagram in Figure 4-19 had to be adjusted slightly for the analytical model. This final analytical formulations are presented in Appendix A. This standard configuration had no initial spring constant since the effect of the initial spring constant had to be determined. The standard configuration for the finger used in all the tests to determine the effect of the different parameters is given in Table 4-1.

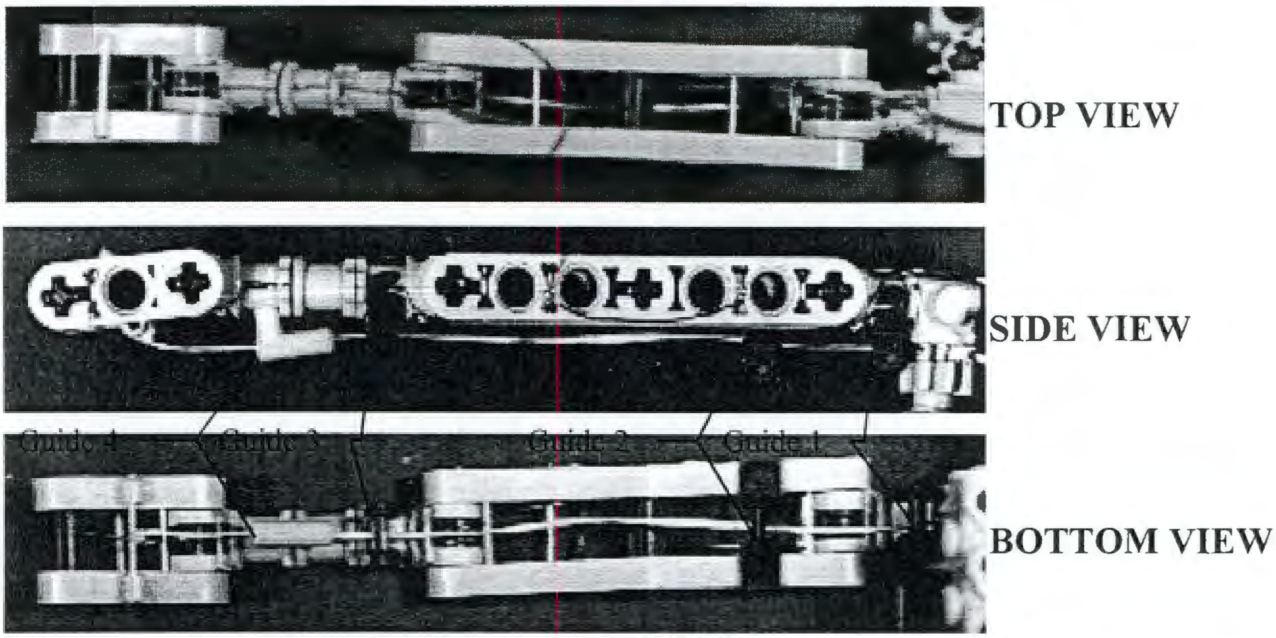


Figure 4-20: Different views of the basic finger configuration.

Digit length:	l_1 = 24 mm	**Stop angle:**	θ_1^{max} = 90°
	l_2 = 40 mm		θ_2^{max} = 90°
	l_3 = 24 mm		θ_3^{max} = 90°
Guide length:	r_1 = 13 mm	**Guide angle:**	β_1 = 25°
	r_2 = 24 mm		β_2 = 20°
	r_3 = 32 mm		β_3 = 12°
	r_4 = 10 mm		β_4 = 40°
	r_5 = 15 mm		β_5 = 0°
Initial spring displacement:	Ω_1 = 0°		
	Ω_2 = 0°		
	Ω_3 = 0°		

Table 4-1: The standard configurations for the finger.

4.6.2.4 Tests and results

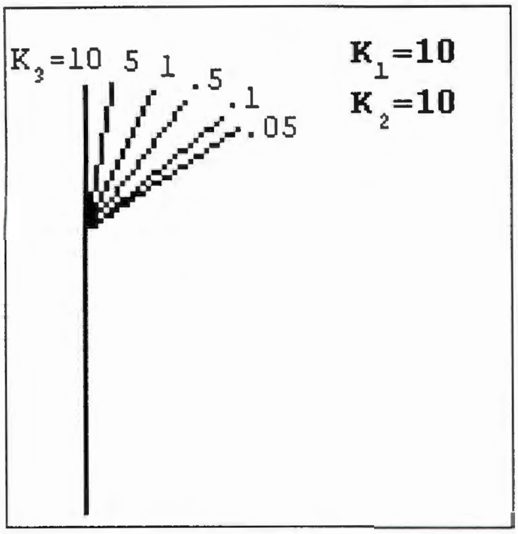


Figure 4-21: The effect of changing the spring constant.

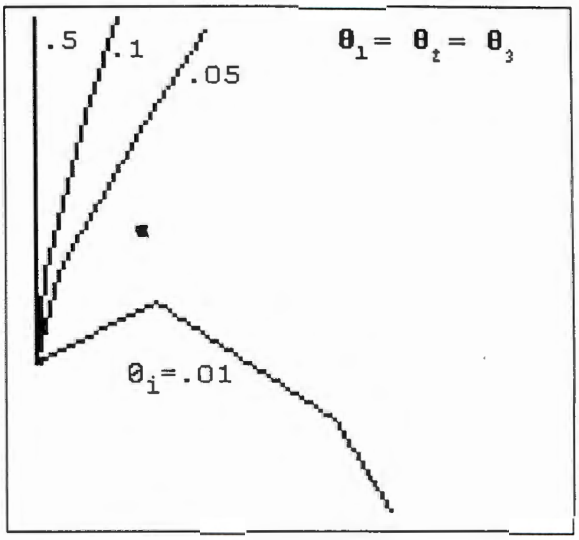


Figure 4-22: Finding the optimal spring constant.

The first step was to determine the effect of *individual spring constants* on the finger trajectory. The spring constant of the distal spring were lowered systematically and from Figure 4-21 is clear that the joint with the lower spring constant are flexed first.

The standard configuration is used to determine the *maximum spring constant* which will cause full closure of the finger for the maximum available force. The spring constants at all the joints were held equal and lowered gradually until the finger reached full flexion at all the joints. The 1N force applied for this test is the maximum available force to fingers from the tendons. From the results (Figure 4-22) the maximum spring constant to cause full flexion of the finger is determined as 0.01 N/rad. This value is used as the standard value for further tests and to determine the basic configuration of the rotational spring.

The next step was to determine the trajectory for the standard configuration of the finger. The configuration was tested with the equal spring constants at each joint to establish a basic trajectory(Figure 4-23(a)) for comparison. To determine the effect of the individual spring constants on the trajectory (Figure 4-23(b)-(d))of the finger the spring constant at each joint was lowered while the others were kept constant at 0.01N/rad. The first observation is as expected; the joint with the lower spring constant always flexes first. The next observation is; to achieve the same relative joint deflection at the individual joints some joints need more substantial lowering of the spring constant than others. This means that some joints are less susceptible to changes in the spring constants than others. The MP are the most dependant on the spring constant followed by the distal IP joint and lastly the proximal IP joint.

The next parameter investigated was the *location of the tendon guides* to see the effect on the trajectory of the finger. The guides were shifted to see how this would change the trajectory of the finger. For the test the radius (r_3) and the angle(β_3) of the distal guide was changed. Figure 4-24(a) represents the superimposed trajectories for the various guide radii and Figure 4-24(b) the trajectories for the guide angles. The trajectories are almost the same for a substantial change in the guide radius. From this can be deducted that a significant change in the guide location is necessary to make a noticeable difference in the trajectory. The dimensions of the finger does not allow considerable variation in the

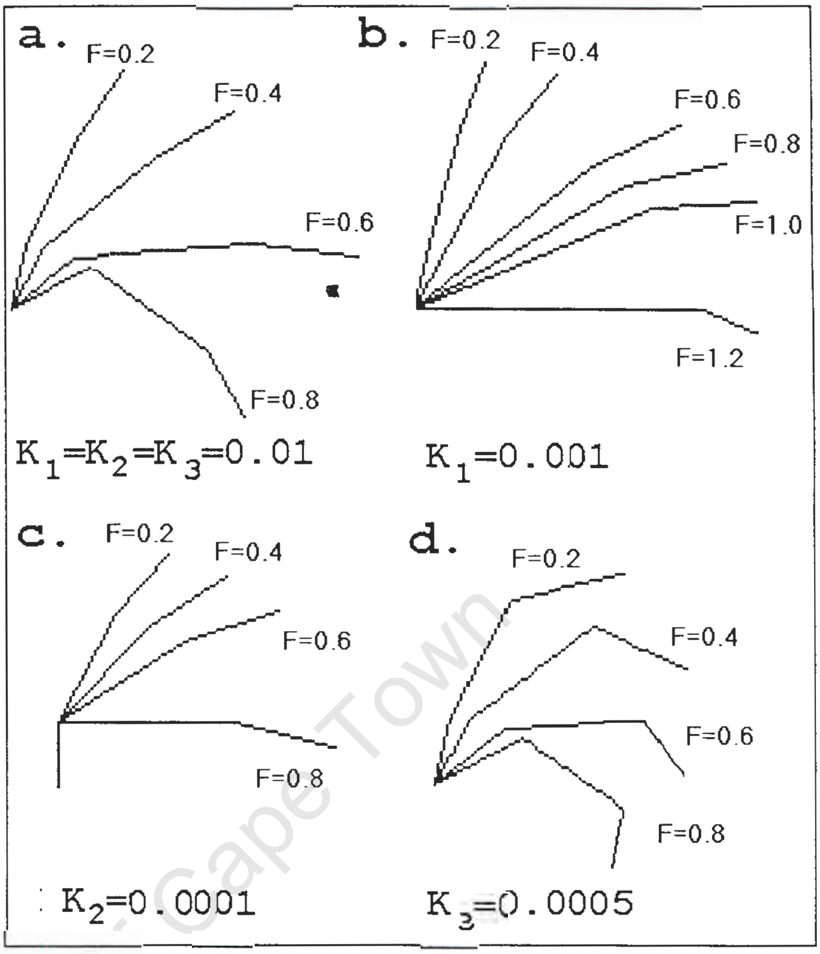


***Figure 4-23:** The effect of spring constants at individual joints.*

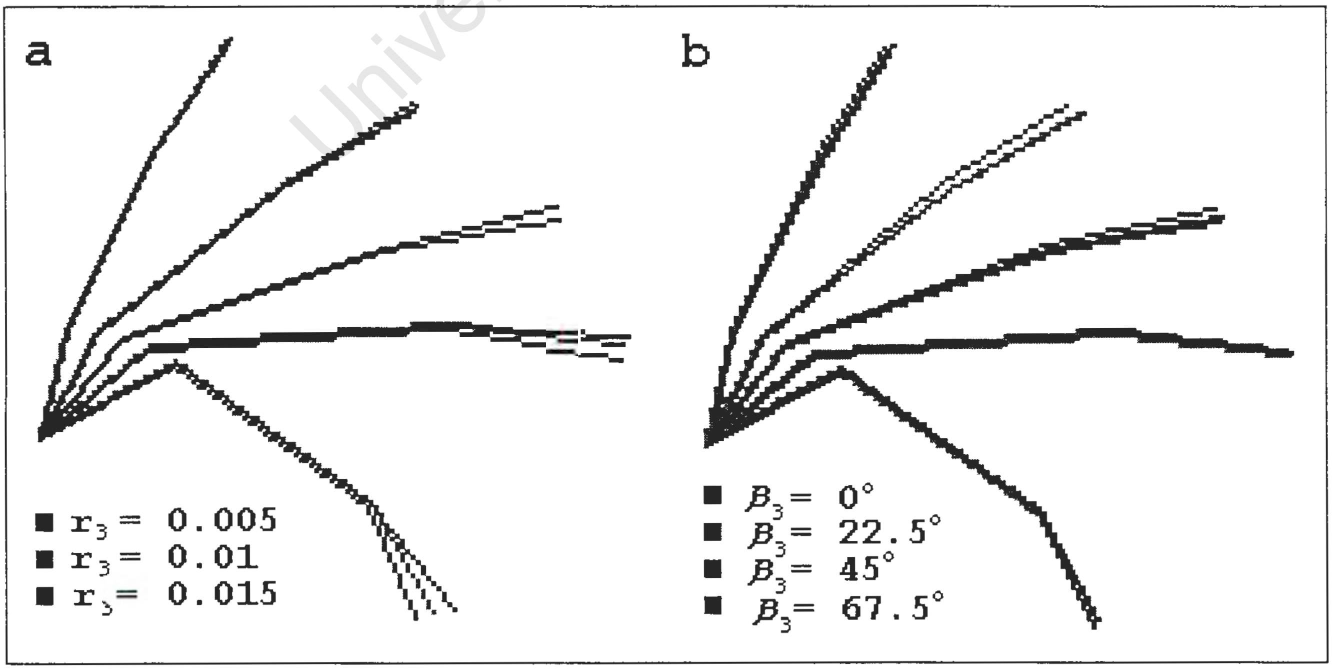


***Figure 4-24:** The effect of a changes in guide location on the finger trajectory.*

location of the guide to avoid interference between the tendon and the object during gripping. It was therefore decided to keep the guides in the standard positions as specified in the initial design because these positions are the most convenient to use and provides the most rigid attachments.

Finally the effect of applying an *initial moment* to the joint was determined. This is done by adding an initial moment only to the two distal springs. In the finger this is practically achieved by applying an deflection to the torsional spring when there is no relative angular displacement at the joint(fully extended). An equal initial displacement was applied to the MP and proximal IP joints to determine the effect on the trajectory of the distal phalanx. The results(Figure 4-25) show that the initial moment has a considerable effect on the trajectory of the finger. The distal IP joint is flexed first because there is no initial deflection or moment in the joint. The joint is flexed until the moment in the joint reaches the same value as the initial moment in the other joints after which all the joints flex together.

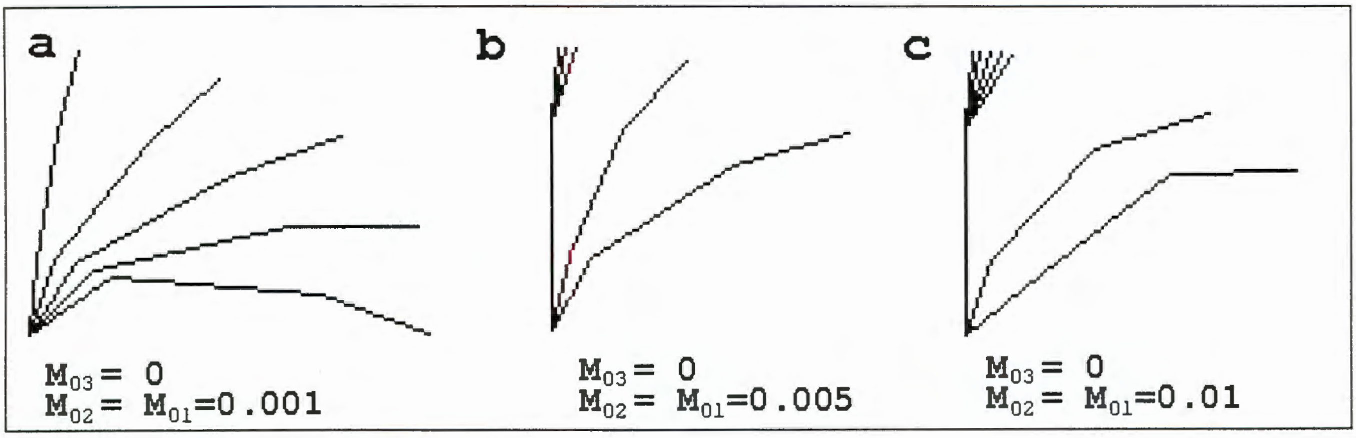


Figure 4-25: The effect of adding initial moments to the joints on the trajectory.

4.6.2.5 Conclusions

The results of the tests led to four very important conclusions;

- The effect of the guide location on the finger trajectory is not very significant.
- Changing the spring constants has a considerable effect on the trajectory with the joints having the lowest spring flexing faster than the other joints during closure. For the standard finger configuration the MP joint is the most susceptible to a change in the spring constant at the joint.
- Adding an additional spring deflection also has a considerable effect on the trajectory with the joint with the lowest additional deflection moving first but only for the initial deflection until equal moments in joints are reached.
- The maximum spring constant at all the joints causing full closure of the finger is 0.01 N/rad.

4.6.2.6 The final finger configuration

The final configuration for the finger was determined using the conclusions made from the tests. The conclusions had to be combined with practical applications of the various mechanisms. A practical torsional spring had to be constructed to fit in the joints. The spring was made out of available steel wire and subjected to a test to determine the spring constant. The spring constant of a torsional spring, k, rotated by a moment, M, through Φ radians is given by:[37]

$$k = M\Phi$$

The spring constant for this specific spring configuration with two complete windings was calculated to be 0.00915(Appendix A). The relationship between the number of windings of a torsional spring, N, and the spring constant, k, is given by:[37]

$$N = \frac{d^4 E}{64 D k}$$

The diameter of the wire, d, the diameter of the spring, D and the Young's Modules, E are constants, simplifying the equation that the windings are relative only to the inverse of the spring constant (Appendix B). The positions of the spring attachments on both sides of the joint (Figure 4-12) necessitates full windings of the torsional spring. The number of full windings producing a spring constant just lower than the required 0.01 N/rad is two windings (Appendix B). The basic spring for each joint was therefore chosen to consist of two full windings with an estimated spring constant of 0.01 N/rad. The spring constants for all the joints are made the same to provide a smooth equal deflection of all the joints through the whole trajectory. All the joints were given an initial deflection of 22.5 degrees to ensure proper extension of the joints when the finger is fully extended. This ensures proper contact at the extension limit switches. Due to the fact that the MP joint is more susceptible to initial spring constants it was given an additional initial deflection of 22.5 degrees to ensure that the joint is the last to be fully flexed and extended. This provides a more natural trajectory simplifying the control of the hand. If the MP is always the last finger to be fully extended, therefore the remaining two joints do not need to have limit switches. The lengths of each finger digit can easily be adjusted and were scaled at 1:1.2 to fit the size of the palm. Since the guide positions do not affect the finger trajectory considerably the second guide was removed and the basic radii and angles for all the guides were kept the same for all the fingers. From the range of motion for the finger joints (Table 2-2) the maximum deflexion for the joints can be estimated to be 90°, therefore the flexion/extension range of the joints were taken as 0-90° to simplify the finger design. The final dimensions of all the fingers are represented in Appendix A.

4.6.2.7 *The final finger closing trajectory*

The closing trajectory for the final design of the index was captured (Figure 4-26) to be evaluated. The finger has a highly cosmetic closing trajectory. It was therefore decided to be sufficient to be incorporated in the developed hand. The results and conclusions obtained from the analytical model proved to be realistic and correct, providing the author with an accurate and methodical approach towards the determining of the finger trajectory.

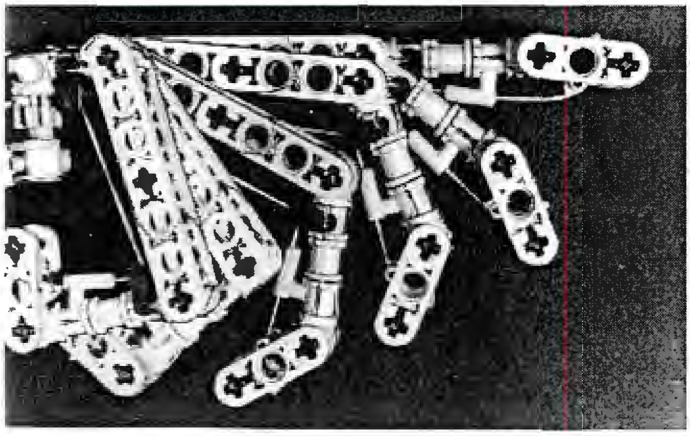


Figure 4-26: The final comparison between theoretic and real trajectory.

4.6.2.8 *Additional design detail*

The flexion and extension *stops* were added to the design as shown in Figure 4-27 ensuring each joint does not exceed its flexion or extension limits. These stops also serve as limit switches to detect when full flexion and extension is reached.

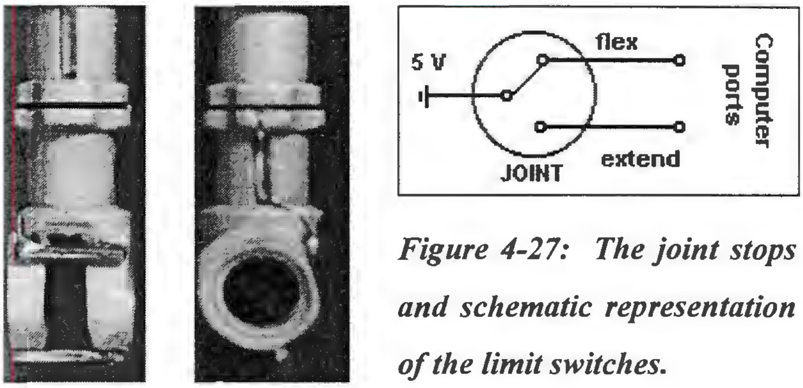


Figure 4-27: The joint stops and schematic representation of the limit switches.

Guides are very important to ensure smooth, low friction sliding of the tendons. The guides also direct the tendons to apply forces at the correct locations and directions. The general approach is to have very smooth surfaces with a low coefficient of friction and to avoid sharp bends. The latter increases the normal forces leading to higher frictional forces. All the guides are shown in Figure 4-28. The MP-guide plays a vital role in that it guides the tendon through the MP joint with the least interference while the finger is abducting or adducting. The guide has rounded edges at both sides guiding the tendon as the joint rotates. The line of action of the tendon across the first and second guides necessitates support only on the palmar side of the hand. This led to the specific guide being used for this purpose because it is easy to stick to the finger member. The changing direction of the applied force on the third compelled support in all directions leading to a different guide choice.

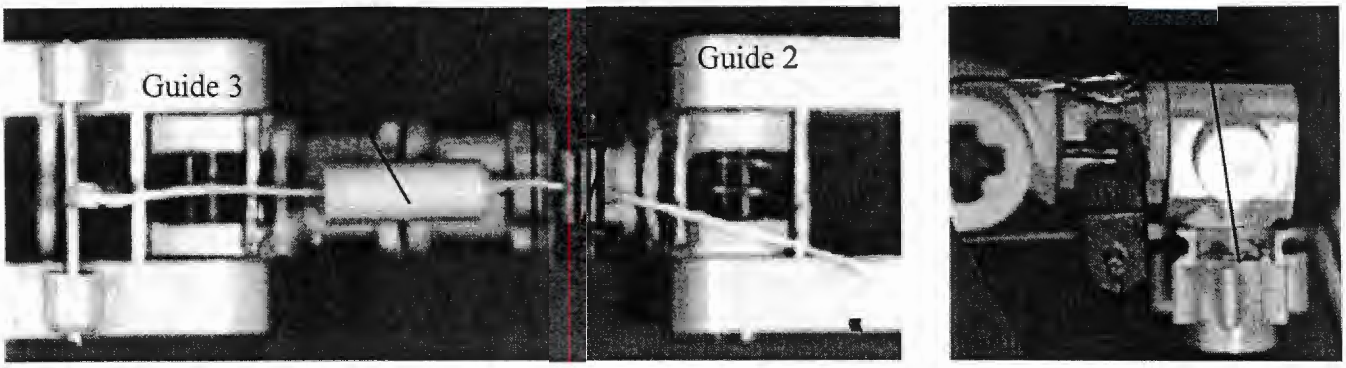


Figure 4-28: The final guide configurations and locations to guide the tendon.

The *springs* need to be attached to the finger on either side of the joint. The spring attachments should be easily detachable to replace springs. The springs free ends should not be fixed rigidly to the finger digits because this introduces an additional moment at the joint. The attachments used in the design is shown in Figure 4-12. On the 'female' side a simple cross pin is used and on the 'male' side a sleeve is pushed over the shaft constraining the spring. The combination of these attachments give the spring the necessary stability but still allows the edges of the spring to slide at the attachments.

4.7 Thumb design

The design of the thumb is very much the same as that of the other fingers. The main difference is that the thumb has only one IP joint and it has an additional rotation mechanism to achieve opposition in the hand. The MP joint of the thumb is essentially the same as the proximal IP joint of the other fingers Figure 4-29.

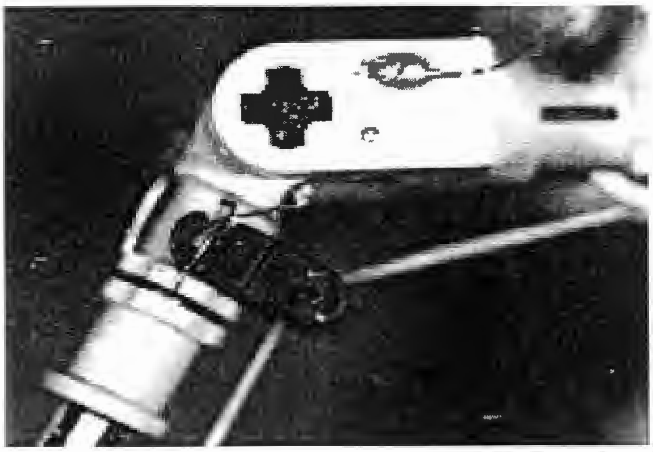


Figure 4-29: The MP joint of the thumb.

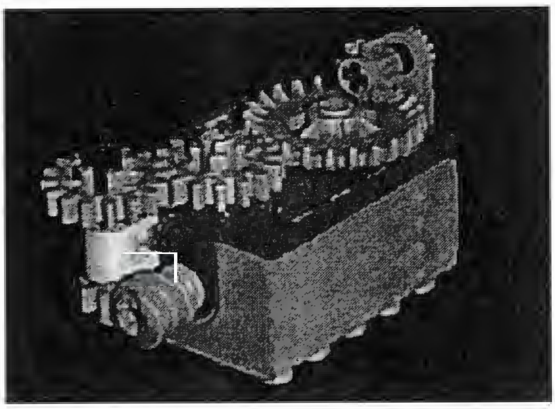


Figure 4-30: The gear rotational concept for the thumb.

The *rotation mechanism* of the thumb is an essential function of the hand. It provides the thumb with an additional degree of freedom making opposition possible for the hand. The mechanism of rotation is not exactly the same as that performed by the thumb and not as functional but is the best that can be achieved without complicating the control considerably. In the hand the motion is achieved by a two-degree-of-freedom joint which is difficult to control. The motor assigned to actuate this motion is located in the back of the palm (Motor D) with its driving axis pointing towards the back of the hand (Figure 4-5). This is some distance away from the actual point of rotation and the motion had to be translated to that point. The first idea to achieve this was to use gears to transfer the motion to the thumb as shown in Figure 4-30. This was considered because the gears could be flattened to consume the smallest possible space in the palm of the hand. The mechanism worked but the inclusion of all the gears introduced play in the mechanism. After reinvestigation of the human hand is was observed that the palm at the thumb is considerably thicker than elsewhere on the palm. This meant that there was sufficient space to incorporate a more spacious mechanism. This led to the decision to employ direct rotation of the thumb through a shaft as shown in Figure 4-33. This mechanism had much higher tolerances and did not take up much more space than the gear mechanism. The shaft is supported at two points for greater stability and has sleeves to constrain axial movement and to ensure it can be dismantled later if necessary. A path for the flexion tendon of the thumb had to be found which would not lead to any interference during thumb rotating, ensuring simultaneous flexion and rotation of the thumb. It was achieved as shown in Figure 4-31 by placing a guide on the rectangular corner of the MP joint and by drilling a hole down the center of the shaft for the tendon to slide through. The actuation of the rotation mechanism is stepped down through the same 64:1 gear box configuration as used for the fingers. The mechanism is equipped with limit sensors detecting when the finger reaches a specific angle. A detailed discussion of the functioning of the sensors follows later in the chapter (Section 4.10). The final thumb mechanism is shown in Figure 4-32.

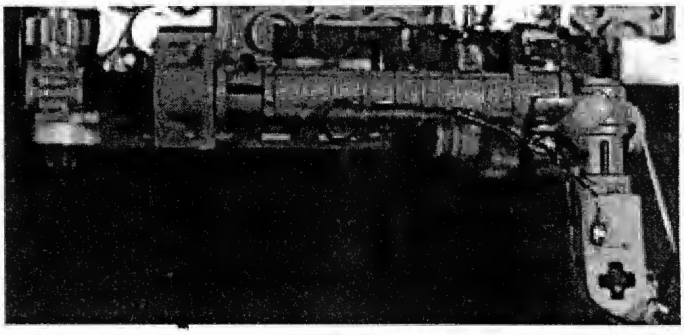


Figure 4-33: The axial rotational mechanism of the thumb.

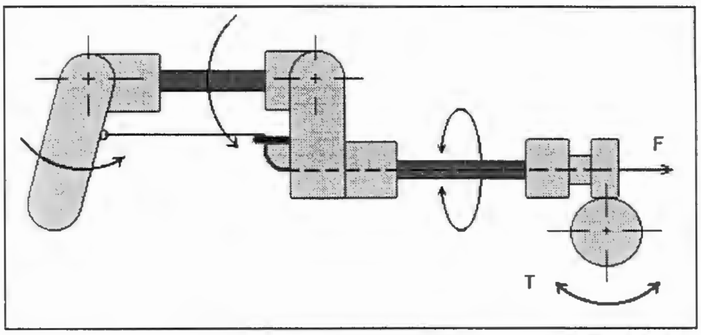


Figure 4-31: Representing the path of the tendon through the thumb.

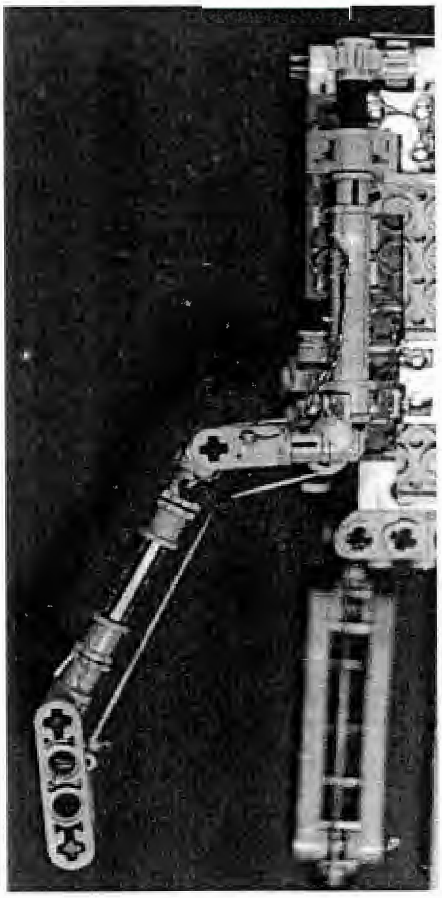


Figure 4-32: The final thumb configuration.

4.8 Abduction Rack

The abduction/adduction of the fingers are important for better gripping of spherical and large objects. Abduction increases the width of the grasping area ensuring good contact with the object. The mechanism aims to achieve the equivalent movement achieved by the human hand. In the hand the middle finger is stationary while the adjacent fingers are rotated away from the middle finger during abduction. The opposite happens during adduction of the fingers. In the human hand abduction of individual fingers can be achieved through conscious control of the fingers. Subconsciously the fingers abduct simultaneously with the index and ring finger abducting at the same rate and the little finger at a quicker rate. This ensures that the fingers are spread evenly along the gripping surface. Measurements from the human hand shows the maximum abduction angle for the index and little finger is 40 degrees and 20 degrees for the ring finger. This means that the index finger abducts at approximately double the rate of the index and ring finger.

The author tried to achieve the abduction motion by linking all the fingers through *gears* providing the correct gear ratios as well as directions (Figure 4-34(a)). Driving any of the fingers would result in the actuation of all the other fingers. The limited space between the fingers and the fact that the distances between them could not be changed led to problems in the design. The Lego gears are only available in specific sizes which can not be adjusted to fit the required dimensions for the mechanism. Another negative aspect of the mechanism is that torque will dissipate through the gear train as it is transferred from the one gear to another. This will lead to low efficiency of the system and to less power in the fingers at the end of the gear train.

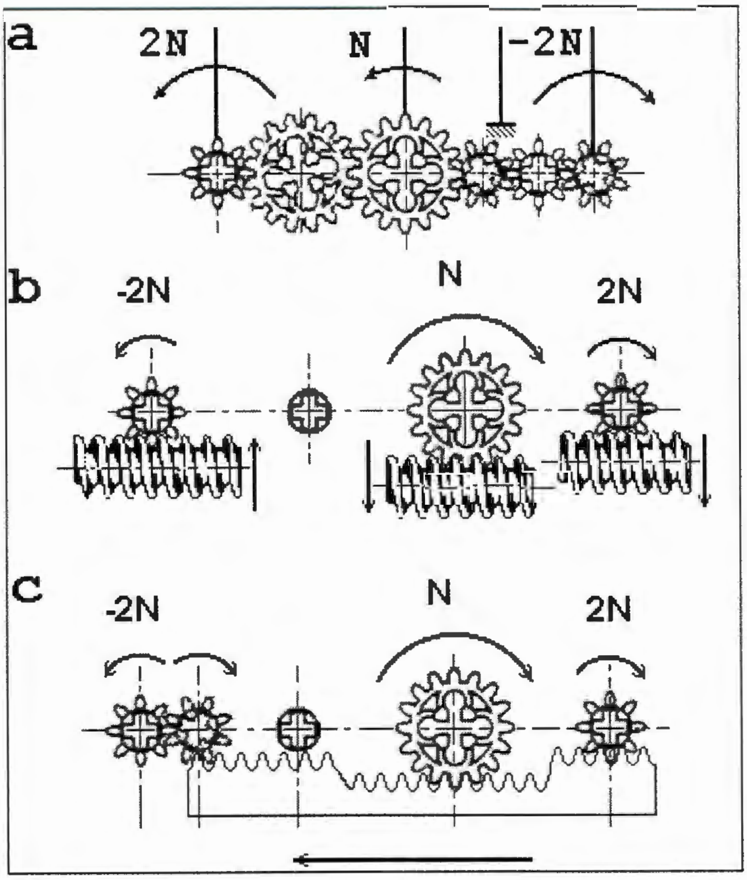


Figure 4-34: Various abduction rack concepts. abduction rack using a gear train.

An improvement on this system is to fit each finger with a gear with the right gear ratio and then driving it through a single gear mechanism. Using a *worm gear* system was considered (Figure 4-34(b)) to achieve this task. The large diameter of the worm gear as well as the fact that the different fingers would need different size worm gears or a different axis for each worm made the use of worm gears impractical.

The substitute for the worm gear was found in the *gear rack* (Figure 4-34(c)). The rack fits perfectly into the available space and could be cut to fit the different sizes of the abduction gears. The rack transmits the forces directly to each finger reducing the losses to a minimum. To achieve the correct ratio between the fingers during abduction the index and little finger was each fitted with an 8 tooth gear and the ring finger with a 16 tooth gear. This provided the index and little finger with twice the abduction speed as the ring finger. The middle finger is rigidly fitted to the hand and not connected to the mechanism. The index finger was fitted with an additional gear with the same size next to it. The rack drives the index finger through this gear inverting the direction of the motion ensuring the motion of the index finger is in the opposite direction from the other fingers. High tolerances on the fitting of the rack and smooth gliding surfaces is important to ensure effective and smooth force transmission.

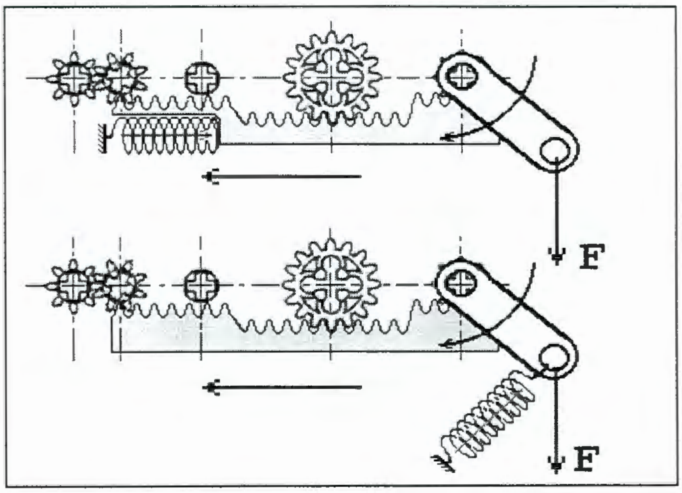


Figure 4-35: Actuating the abduction rack with a tendon.

The motor assigned to actuate the abduction of the fingers is located in the back of the palm with the driving shaft pointing towards the back of the hand. This meant that the rack had to be actuated remotely across the palm of the hand by using the least space and without interference. The first method was using a tendon to move the rack. A lever arm was connected to the rotation axis of any convenient finger. The tendon would pull the arm and rotate the finger which is connected to the other fingers through the abduction rack, thus rotating all the fingers. The tendon can only apply a force in one direction which meant a spring system had to be included to actuate the rack in the opposite direction. The spring can either be connected to the lever arm directly or to the abduction rack as shown in Figure 4-35. The lack of sufficient space in the palm as well as the possibility of interference between the object and the tendon cancelled the use of the lever system. The mechanism considered introduced an actuation through a steel shaft(Figure 4-36) along the palm of the hand. The shaft runs underneath the floor board

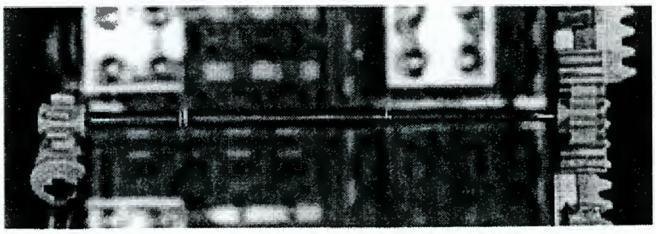


Figure 4-36: The iron shaft in the palm driving the rack.

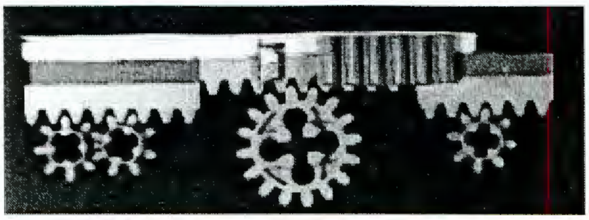


Figure 4-37: The abduction rack configuration.

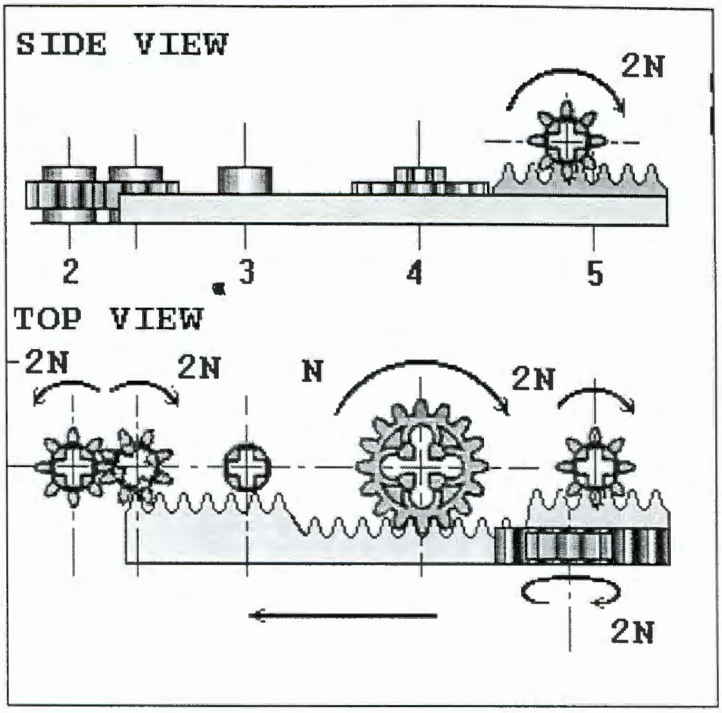


Figure 4-38: Schematic representation of the abduction rack.

of the palm which is grooved to provide the necessary support for the shaft. The shaft has an 8 tooth gear on each side being driven from the motor on the one side and driving the rack on the other end. Another rack was added(Figure 4-37 and Figure 4-38) to the previous rack on the bottom surface to be driven by the shaft. The bottom rack glides in a groove made in the floor. The rack is fitted with a stop on each side to stop the fingers at their abduction or adduction limits. This abduction mechanism provides an easy and robust way of driving the abduction rack. The system is bi-directional and is not prone to interference in the palm of the hand.

4.9 The 3-finger differential

In the human hand the last two fingers are not as essential to the gripping function as the first two fingers. This causes the last three fingers to have a coupled motion during normal gripping functions. This was the reason why one motor was assigned to flex these three fingers simultaneously in the prosthetic hand. The objective is to drive all three fingers semi-independently which means that while none of the fingers are touching the object the fingers should close simultaneously having the same closing trajectory. If any of the fingers touch the object the others fingers should be able to keep on moving until they reach their limits or touch the object. To achieve this, various mechanisms were tested to determine the most efficient and robust one.

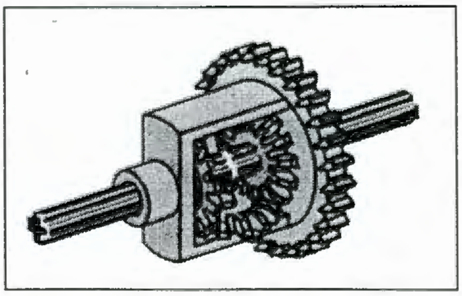


Figure 4-39: A Lego differential.

Lego has *differentials*(Figure 4-39) which was a consideration for the design of the mechanisms. These differentials are exactly the same as used in the driving axis of a car. The differential ensures that the sum of the output torque's at the output shafts are always the same. Using a combination of these differentials as shown in Figure 4-40 will keep the sum the three output torque's the same. If the fingers were driven through these shafts the torque would always be equally distributed between the fingers. Unfortunately these differentials were too big to fit into the hand and could not be used.

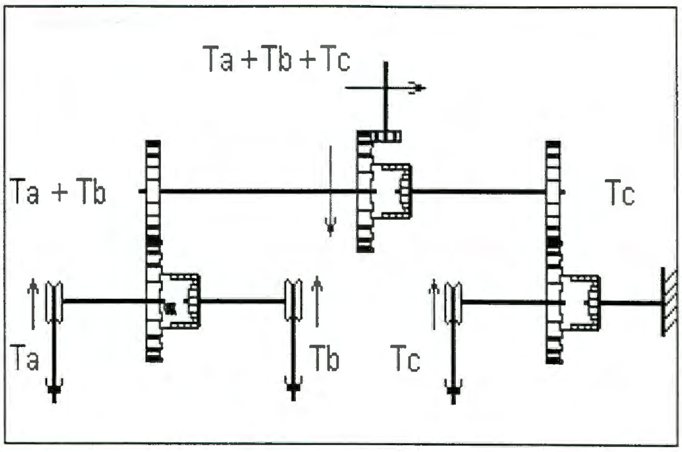


Figure 4-40: Achieving independence in the fingers using the Lego differentials.

The next mechanism considered was the mechanism used by Crowder.[4] It uses the equalising bar as a differential to simultaneously actuate the three fingers. This is the same equalising bar principle used by Crowder to actuate the finger joints and is explained in Chapter 3 (page 32). The mechanism, shown in Figure 4-41 uses the equalising bar to distribute the actuation force of the motor equally to each finger. This will ensure that the fingers not touching anything will keep on closing until the all the fingers touch something or reach their limit then the force applied by all the fingers will be kept equal. This is an effective and simple way of achieving the differential system but Lego do not have very flat components which will lead to a very spacious mechanism. The nature of the space consumed by such a system did not suite the space assigned to it by the design of the rest of the hand.[4]

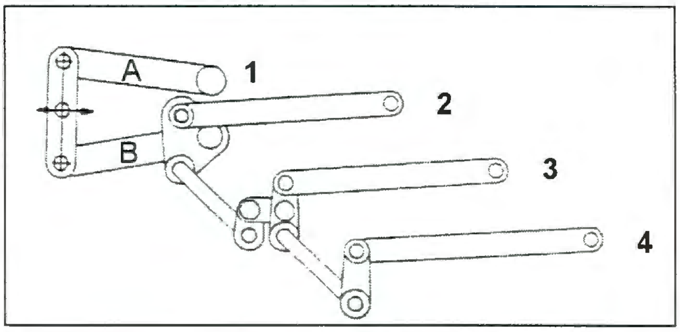


Figure 4-41: The Crowder link-bar differential mechanism.

Another mechanism considered was variations in *clutch mechanisms* (Figure 4-43(a)). The basic principle is to have all the finger tendons attached to separate pulleys. Part of the driving shaft is threaded with a nut screwing onto it. The nut has a pin which fits into a groove parallel to the shaft, allowing the nut to move axially along the shaft with the direction depending on the direction the shaft rotates. The in-screwing nut compresses a spring which in turn increases the pressure on the side of the pulleys. The discs between the pulleys can slide longitudinally along the shaft but forms a solid connection for transmitting torque. An increase in pressure of the spring compress all the pulleys and the disks between them, increasing the pressure on the sides of the disks and therefore the torque transmitted to the pulleys. This system would allow the fingers touching an object to slip while the others keep on

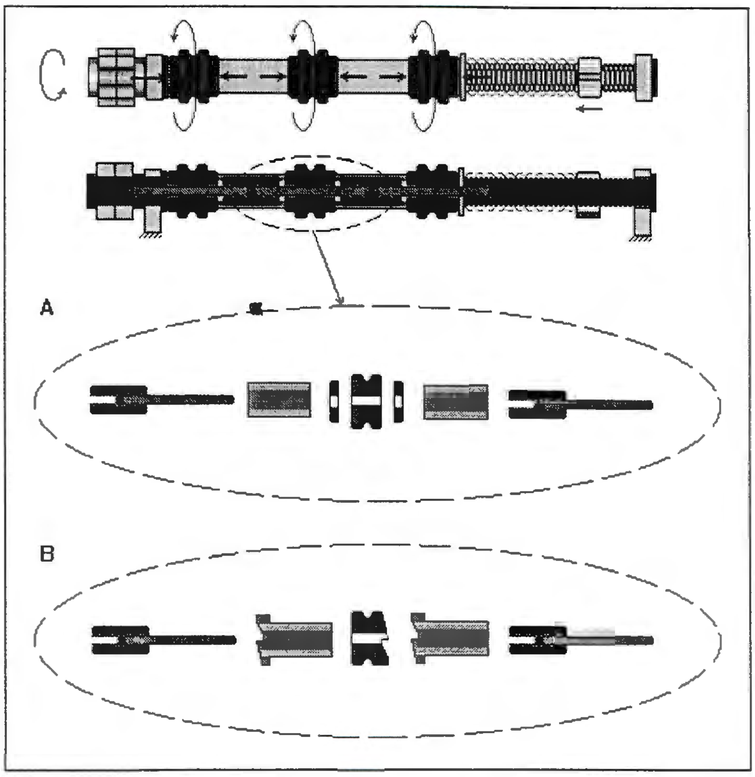


Figure 4-43: Concepts for clutch mechanisms driving the 3-finger link.

closing. As a result of the spring constantly being compressed by the nut the force increases constantly during the closure of the hand to ensure a strong grip on the object. This design has a few complicating factors. The first problem is that energy which should be used to flex the fingers is wasted in the attempt to make the fingers independent. This energy is absorbed by compressing the spring and becomes crucial when the large forces have to be transmitted because it means a large axial force is needed. The other problem is that the hand does not always achieve the same final force on the object since the nut is not always woud up the same distance. Another problem is that the spring could reach its compressive limit stalling the motor before the object is properly gripped. This could be avoided to an extend by having the nut reach the end of the groove as the spring limit is reached stopping the nut from winding up further. This was achieved by replacing the sides of the groove at this end with a ratchet mechanism (Figure 4-42) which will allow the nut to turn freely when this limit is reached without screwing the nut in. When the shaft changes direction the ratchet will guide the pin of the nut back into the groove unscrewing it. A similar device at the other end ensures the nut stops unscrewing before the motor stalls. Problems are encountered when slippage occurs during the grasping motion. This causes the nut to screw in extensively but when the object is released it opens the finger not allowing the nut to screw all the way back to where it started from. There is no easy mechanical way of rewinding the nut to where it started from at full extension without changing the direction of the finger. The tendon connection to the pulley causes the finger to start closing again if the tendon has been fully unwound because the pulley starts winding the tendon in the opposite direction. This will mean that eventually after a few closures the nut will be wound up to its maximum when the finger is still open. These complications led to the design being rejected. A variation of the system could be to replace the nut and spring with two toothed discs as shown in Figure 4-43(b). Turning of the shaft in one direction would cause the teeth to slide relative to each other increasing

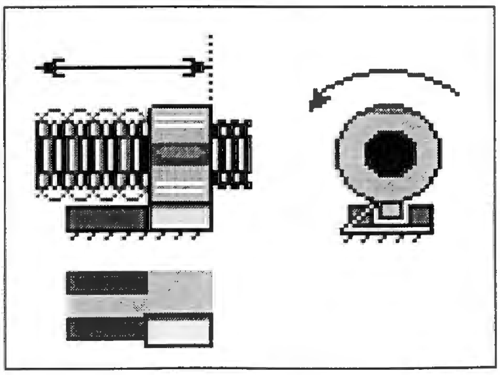


Figure 4-42: The ratchet mechanism.

the distance between their opposite ends and hence pressurising the discs. Rotation of the shaft in the opposite direction will cause the teeth to grip again and form a quick release of the fingers. To be effective the mechanism has to be activated only as the finger reaches the final gripping stage on the object. To detect this final stage using mechanical system proved to be impractical.

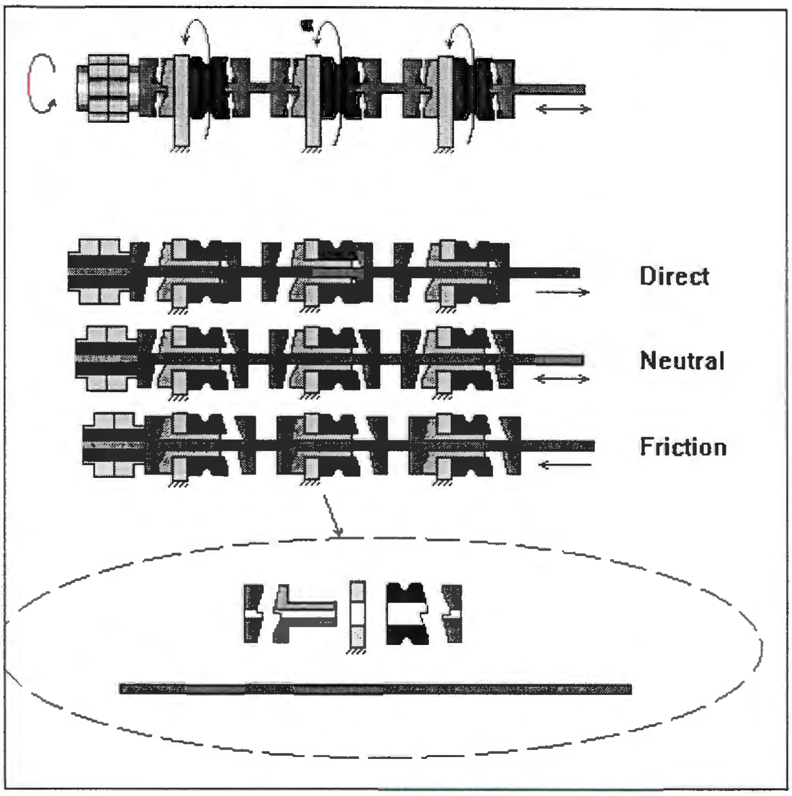


Figure 4-44: Achieving independence in the 3-finger link using a gear mechanism.

The next mechanism considered was the *gear mechanism* (Figure 4-44). Again there are a few variations of this mechanism but the basic principle remains the same. The basic principle is to have different gears for different stages of the grasping action. The design includes a neutral gear, a direct gear and slip gear. In the neutral state the driving shaft is not connected to the pulley allowing no torque to be transferred to the pulleys. The direct state connect the driving shaft directly to the pulley forcing all the torque in the shaft to be transmitted to the pulleys. The slip state connect the drive shaft through a friction slip connection to the pulleys allowing a certain slip force to be transmitted to the pulleys. This means that less torque is applied to the pulleys than was applied to the driving shaft. With the shaft in the middle position none of teeth of the shaft on either side of the pulley is engaged with the pulley representing the neutral state with no torque transmission. Moving the driving shaft towards the left causes the teeth of the shaft to the right of the pulley to engage with that of the pulley itself. This causes a direct torque transmission between the shaft and the pulley. Moving the shaft to the right engages the teeth of the shaft on the left of the pulley with a hollow shaft on which the pulley can slide with considerable friction. As a result only part of the torque applied by the shaft is transmitted to the pulley. The slide state is used with initial closure of the fingers with the slipping feature allowing all the fingers to touch the object. The mechanism is then switched into the direct mode to apply the force directly to all the fingers until the appropriate grip force is reached. To release the grip the mechanism can be switched into the neutral state allowing the fingers to open without transferring any torque to the shaft or the hand can be kept in the direct state and the direction of the shaft reversed. Switching from one state to the other created a problem because all

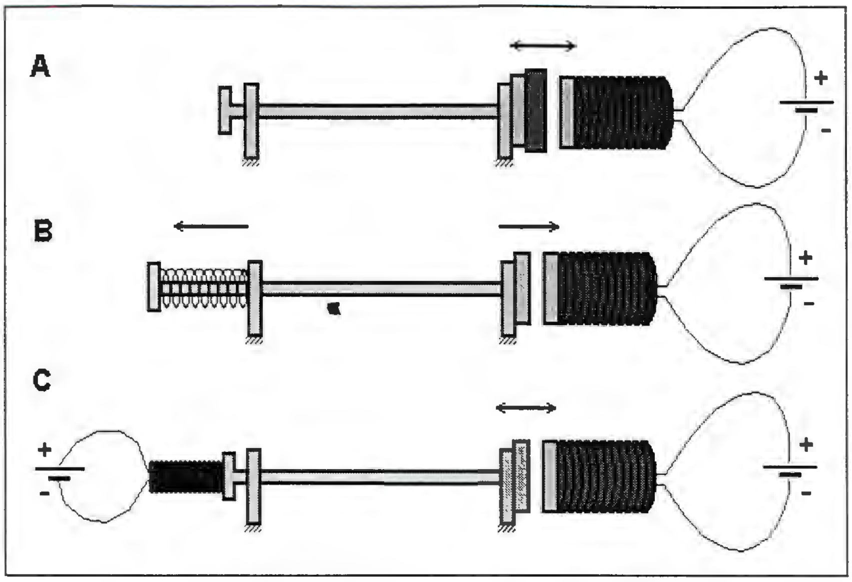


Figure 4-45: *Using an electromagnet for switching gears.*

the available actuators have been used for other purposes and a substantial force is necessary to switch the gears. Using a one directional electromagnet attracting the metal shaft against a spring (Figure 4-45(a)) or using a two directional electromagnet to attract or push away a permanent magnet fixed to the shaft (Figure 4-45(b)) was considered. Another method as shown in Figure 4-45(c) is to, instead of the permanent magnet magnetise the shaft using an electromagnet. The latter was designed and tested but had a few problems. Manufacturing an electromagnet using the 9V and 200 mA output of the Lego interface box strong enough to switch the gears and small enough to fit into the available space is very difficult. It has to be strong enough to switch the gears from the slip stage past the neutral state into the direct state without the hand releasing the grip. The other question was which gear teeth to use. The regular teethed gears supplied by Lego (Figure 4-46(a)) has slight friction between the teeth making it difficult to engage or disengage. The teeth are also very small and if the tolerances on the whole mechanism is not extremely high the teeth do not always engage. To make the teeth easier to engage some of the teeth were removed (Figure 4-46(b)) to reduce the friction during engagement but the system was still too fragile. This was partly overcome by using angled teeth (Figure 4-46(c)). Using less and more widely spaced teeth (Figure 4-46(d)) increases the possibility of the gears engaging successfully but allowed the teeth to rotate more before they are engaged, releasing the grip in the object. All the variations of the mechanism proved to be too fragile to employ practically and were rejected. The mechanism had to be more simple and robust to incorporate in a real prosthetic hand.

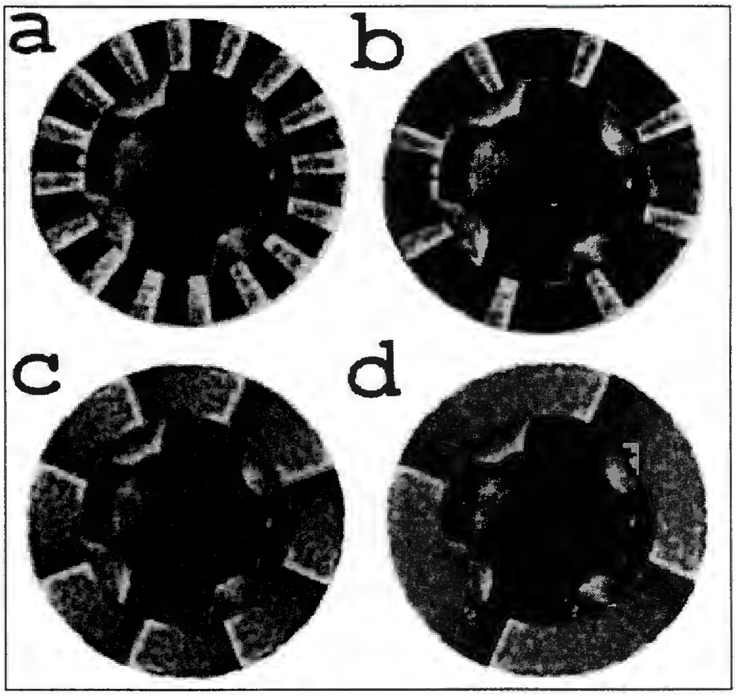


Figure 4-46: Different types of gears to use in the gearbox.

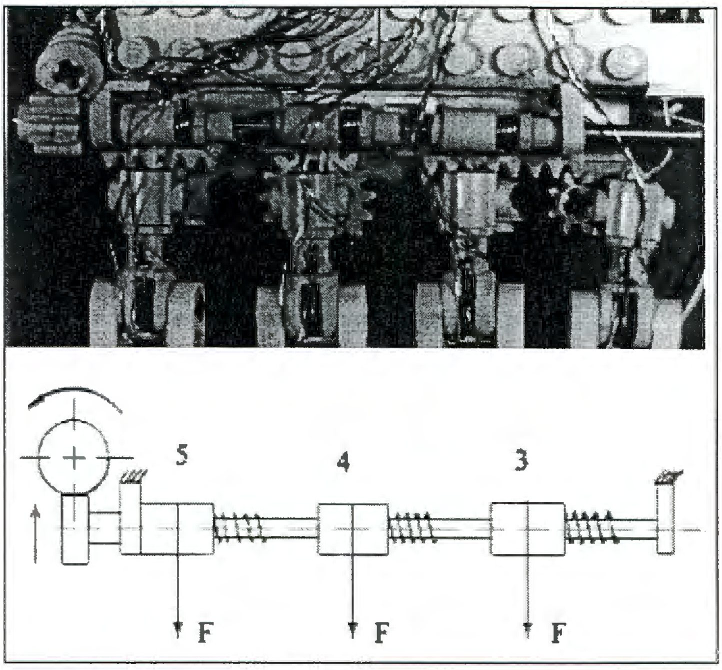


Figure 4-47: The final 3-finger link mechanism incorporated in the design.

A mechanism incorporating some kind of *elasticity* in each finger allow for flexibility of the individual fingers improving grasp considerably. The first option is to connect elastic bands in series with the tendon allowing the tendon to stretch when the individual fingers reach an object while the other fingers still close. Incorporating this into the finger is problematic due to the space restrictions between guides. Allowing the elastic parts to slide over the guides would affect the finger motion because of the higher friction between the elastic band and the guides. The bands have to be fitted between the guides with enough space to allow for the movement relative to the guides during closure. This problem is solved by replacing the elastic bands with torsional springs at the tendon pulleys. The one end of the torsional spring is fixed to the shaft and the other end to the pulley. The torque of the shaft is transmitted to the pulley and therefore also to the finger through the spring. This allows the fingers to close simultaneously if none of the fingers touch an object. Once any of the fingers makes contact with the objects the torsional spring deforms allowing the driving shaft to remain turning, thus flexing the other fingers. Additionally the mechanism has an advantageous automatic locking system when the force in the finger reach a specific limit. The original diameter of the spring is larger than that of the driving shaft but as the spring is tensioned the diameter decreases. When the force reach a specific limit the diameter is the same as that of the shaft preventing any further deformation of the spring and causing a direct transmission between the shaft and the pulley. This mechanism is advantageous in the design of prosthetic hands because it allows flexibility up to a specific force limit which can be determined by the designer and then ensures a high final grip due to the direct force transmission. The whole mechanism is very robust and simple to manufacture. The final design of the mechanism is shown in Figure 4-47. The fixtures on the shaft are pinned to make the mechanism easily interchangeable. The mechanism is driven through the same 64:1 gearbox configuration used as in all the other actuators. The pulleys are arranged on the shaft so that the little finger closes a fraction earlier than the ring finger and the latter a fraction before the middle finger. This provides a more natural flexion pattern, with the hand closing from the outside inwards. It is achieved by rotating the attachment of each torsional spring on the driving shaft through 20 degrees which cause the pulley on the outside of the hand to start tensioning the tendons before those on the inside. For the limit sensors to detect when the fingers reached the extension limit the limit switch has to make contact long enough for the software to detect the full extension and switch off the motor. If the motor is not switched off in time the tendon is wound up on the finger in the opposite direction. The tendons are connected to the pulleys allowing some slack after the fingers have reached full extension. This causes the pulleys to still be winding off after full extension is reached without immediately closing the fingers again allowing time for the limit switches to detect full extension. From the moment the fingers are fully extended the tendon should be slack for half a rotation.

4.10 Control

In a real prosthetic hand the control of the hand is compressed into very small circuitry which can be fitted into the hand itself. The circuitry receives input from the user as well as all the sensors on the hand using it to control the outputs to the actuators and feedback to the user. In the developed model the control achieved by the circuitry is replaced by computer software. The software receives input from the hand through the computer ports and from the user through the software interface. These inputs are evaluated by algorithms written in the software to control the actuators in the hand by means of the computer ports.

4.10.1 Control mechanisms

4.10.1.1 Outputs

The outputs to control are the current and the direction of the five motors used to actuate the different mechanisms of the hands. This is achieved by using the software and the available Lego subroutines to control the Lego interface box. The interface box is a serial port connection with built in timers. This is ideal for controlling the timing and torque supplied by the motors. The motors are connected directly to the interface box which supplies a working potential and current as determined through the software.

4.10.1.2 Inputs

The inputs to the hand are received from the limit switches in the fingers as well as the current sensors. Lego has various input sensors(Figure 4-48) which were considered for use in the hand. The angle sensors could have made the control of the hand more impressive because it provides an analogue value for the angle of the shaft through the sensor. This would make very accurate positioning of joints possible but unfortunately all of the Lego sensors were too big to use in the design of the hand. Additionally the angle sensors can only detect angle increments of 22.5 degrees which is not sufficient for use in the hand. The touch sensors supplied by Lego could not be used because the size of the sensor. These sensors also rely on contact at a specific point on the sensor while for a sensor to be effective on the tip of the finger it should detect contact over the whole finger surface.

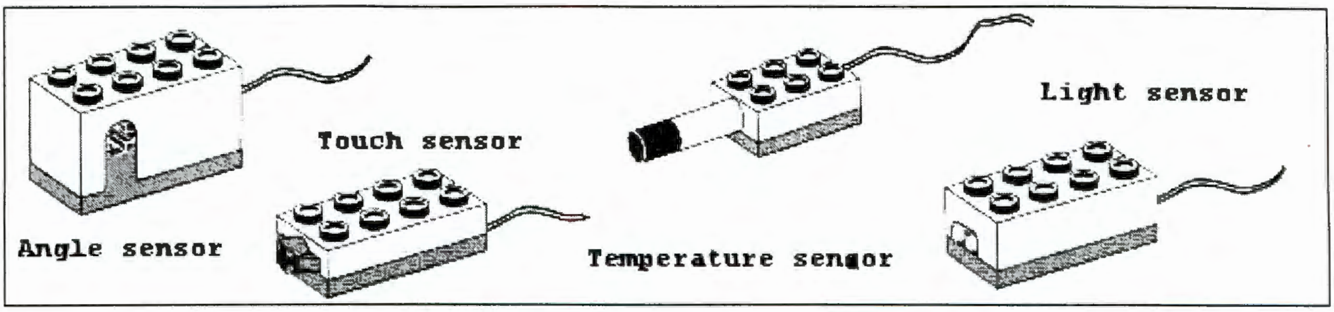


Figure 4-48: The Lego input sensors.

The author decided to use *binary* contact switches to detect the position of certain members of the hand. Binary switch are easy to control and have a very simple design.[8,28] The sensors only provide an open/close signal but this is sufficient to control all the important functions of the hand. An additional input/output interface card connected to a parallel port is used to detect the binary inputs (See Section 4.4.3). Having too many inputs would make the control of the hand very complicated and very slow. It would also be impractical to use in a real prosthetic hand because the computing abilities of the circuitry in these hands is not as powerful as a personal computer. Switches are also fragile and increasing the number of switches increases the possibility of something going wrong.

Through a careful process of elimination the inputs were reduced to a minimum. Having a switch on each joint detecting when it is fully flexed or extended will produce a sum of 28 switches requiring 28 inputs. Connecting the three flexion switches as well as the three extension switches in series for each reduce the inputs from 6 per finger to 2 inputs per finger and a total of 10 inputs for the hand. Instead of detecting the limits for all the joint individually this arrangement will detect when all three extension or flexion switches has reached the limit. This arrangement was reduced further and made more reliable by reducing the sensors to only one extensor switch on the MP joint of each finger. The MP joint is the last joint to be flexed and the last to by fully flexed. Since the control only depends on detecting full flexion or extension of the finger the use of the other switches was unnecessary. All the flexion switches were rejected because the force sensors were introduced to measure the force in the fingers and would detect the motor stalling when the flexion limit for each finger is reached. This reduced the inputs of the hand to 5 for detecting flexion and extension in the hand. The author decided not to introduce limit switches for detecting the abduction and adduction limits because the motors can be switched on for a certain time which is sufficient for abducting or adducting the fingers to the limit and switching it off after a short time period. Three limit switches are used to detect the rotation angles of the thumb bringing the total number of switches used in the hand to 8.

These sensors are divided as follows:

- Switch 1-5: full extension of fingers 1 to 5
- Switch 6: thumb rotated at side of the hand (0°)
- Switch 7: thumb rotated to oppose the index finger (90°)
- Switch 8: thumb rotated to oppose the middle finger (110°)

To simplify the design of the finger the stops of the joints are used as the limit switches (Figure 4-27). The stops are made out of metal and connected to wires, providing the inputs to the computer. The circuitry to provide the correct signal for the input card as well as the connection diagram for the connection to the interface box are provided in Appendix C. The circuitry produce a 5 Volt input potential to the correct port of the input card when the switch is open and a zero potential when it is closed. The mechanism for detecting the rotating position of the thumb is shown in Figure 4-49. It consists of one metal plate on the rotating part of the joint and three plates on the stationery part. The two plates serve as the stops for the thumb and at the same time as limit sensors detecting the 0° rotation and the 110° rotation position. The plate detecting the 90° position has a light spring action and makes contact with the moving plate over the whole range from 90° to 110° providing a closed signal over the whole range. These plates are connected to the ports of the computer in a similar fashion as the extension switches.

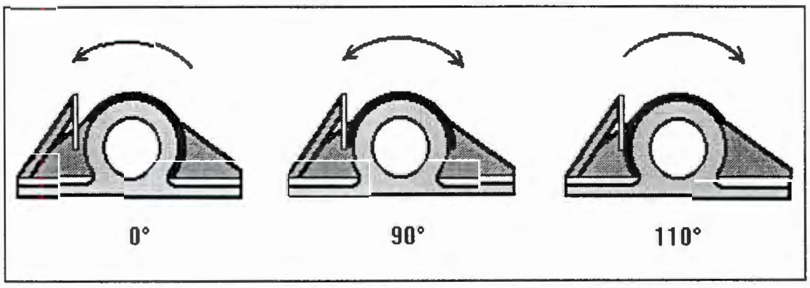


Figure 4-49: The rotation sensor of the thumb.

In previous developed hands the *analogue* measurement of the motor currents have been used in feedback loops for the force control of the hands[20,23]. The same principle is incorporated in the developed model in a simplified application. An increase in the delivered torque by an electric motor leads to an increase in the current drawn by the motor. Test performed on the motors reveal a linear relationship between the torque supplied by the motors and the current utilised by the motors (Appendix A). The current reaches a maximum value when the motor stalls, called the stall current. Leaving the motor in this stalling state decreases the life of the motor and wastes energy without doing useful work which is crucial in real prosthetic hands where energy conservation is essential. It is therefore advisable to switch the motors off whenever they stall while gripping an object. This will protect the motors and concerve energy consumption. Another use of the current indicators is using them as force sensors in the fingers. Since the torque delivered by the motor is relative to the current drawn by the motor, as shown in Figure 4-50, it can be used to get an indication of the force in the finger. This can be used to grip different objects with different gripping forces like gripping an egg without breaking it and gripping a hard stone without dropping it. The finger is closed until the force/current limit is reached and is then switched off. This current is a analogue value and has to be measured by the Lego interface box. The problem is that the outputs and inputs of the interface box have a common power source and are not allowed to be interconnected. Since the motors are already connected to the outputs of the box their currents could not be measured directly by the input side. Circuitry using a separate power supply was incorporated to measure the currents in the motors. The best way to achieve this is to use Hall-detector sensors. Hall-detectors work on an electromagnetic principle measuring the electric field around a wire. The magnetic field around a wire is relative to the current inside it. Putting one of the wires of the motor through the Hall-detector therefore produce an output current which is relative to the current drawn by the motor. The output of the sensor is the connected to the input ports of the interface box and an analogue value is read by the software. The circuitry to incorporate the Hall-detectors into the system is shown in Appendix A. The sensor is sensitive to the direction of the flow of current in the wire giving a positive value in one direction and a negative value in the other. The inputs of the Lego interface can only represent a positive value in the correct current range, representing it with a relative analogue value from 0 to 1019. This means that the detectors can not detect the extension force in the motors and have to be connected carefully to produce a positive value during flexing. Three Hall-detectors were connected to each of the three motors used to flex the fingers. The input values from these sensors are relative values representing the force in the fingers. The magnitudes are not absolute values but depend on each detector, the specific motor the geometry of the finger and the specific circuitry and can therefore not be used to compare different fingers or make force calculations

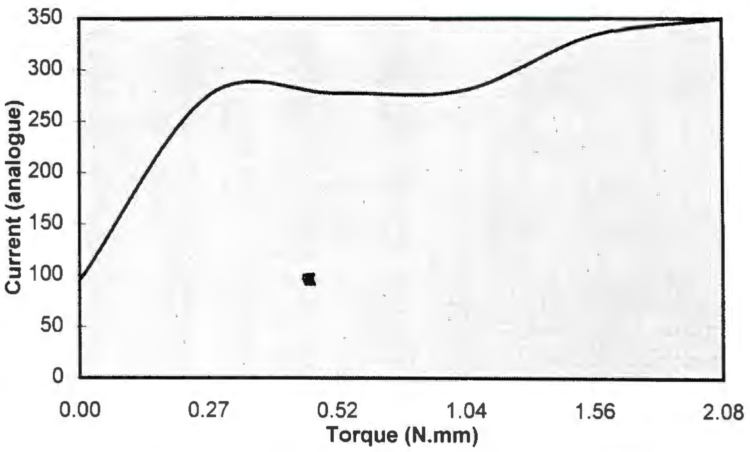


Figure 4-50: The current versus torque curves for a Lego motor as detected by the Hall sensors.

Various touch sensors have been used by previous designers varying from binary contact switches to complex texture detecting sensors.[8,28] The use of these touch sensors can be justified for the use in robotics but not for use in prosthetic hands because of the additional control systems necessary and the lack of proper feedback to the user to utilise the additional information provided by these sensors. Currently the only practical sensor is a binary touch sensor on the tips of the finger or on the palm of the hand. These sensors can be used as described in Section 3.5.2.2 to provide lower level input signals to control algorithms of the hand. The touch sensors immediately available to the author was binary micro contact switches, strain gauges and piezoelectric material. The circuitry for the latter two would lead to a lot of additional circuitry making it less favourable. The piezoelectric material is also better for detecting dynamic forces, in other words for the detecting of a change in force an not the force itself. The material does not supply a continuous signal but one which fades after a change in the applied force was detected. The use of a touch sensor only justifies itself if it provides additional functionality to the hand without introducing too much additional circuitry. A binary contact switch was developed as shown in Figure 4-51 to determine the additional function it provides. A contact switch that can only detect touch in one direction does not justify its use because this can be detected by the force sensors in the hand. The sensor therefore has to detect touch in various directions which necessitates a more complicated, heavy and fragile design. The additional function provided by the designed touch sensors was not enough to include it into the design of the hand and it was decided to use the force sensors as the only touch sensors because of the effectiveness.

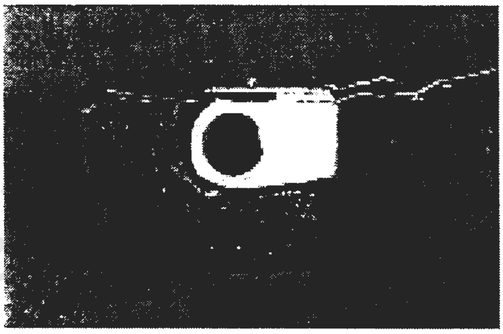


Figure 4-51: A binary touch sensor.

4.10.2 Control strategy

The hand was developed to perform two major functions. The main function is to serve as a concept model for further development as a prosthetic hand and the other is to be used as a educational tool to stimulate children's interest in science. The control strategy for these two functions are very different in that with a prosthetic hand the user is limited to only a few control signals where with the educational tool there is no real limit to the number control signals for the hand, in fact the more controls the better. The control strategy also depends highly on the intellectual level of user and the user familiarity with the program.

4.10.2.1 Manual control

The manual control of the hand is developed mainly to be used by children to play with or by users who are not familiar with the hand and want to see how is works. This mode of control must be straight forward with as many control objects as possible to assist the user and make the use of the hand more interesting. The design of the hand itself is primarily done to be used as a prosthetic hand which does not really suite this mode of control. A very interesting way would have been to enable the user to program the hand to perform certain co-ordinated tasks. This would unfortunately be too complicated for most children because complicated software functions are used to provide the object orientated user interface and to be able to communicate with the computer ports. The most interesting and practical way to use the hand as an educational device to give the user individual control over each motor driving the different parts of the hand. Since the users of the mode of control are very young provision should be made to project components of the hand, especially the actuators. This is done by automatically switching the motors off as the fingers reach their limits in case the user do not stop the motors in time. The sensors of the hand are used to monitor the state of the limit switches and switch the appropriate motors off when necessary. The extensor sensors are used to prevent the fingers from over extending while the force sensors prevent the motors from stalling when the fingers are closed. The rotation sensors prevent the rotation motor from stalling when the 0 or 110 degree limits are reached. The controls should also include an emergency stop which will stop all the motors at once. During the manual operation of the hand the user has control over the following functions of the fingers:

- Thumb flexion/extension
- Index finger flexion/extension
- Combined flexion/extension of last three fingers
- Rotation (opposition) of the thumb
- Abduction/adduction of the four fingers

4.10.2.2 Automatic control

The automatic control of the hand is done in the same way as the control of a multi-fingered prosthetic hand. The prosthetic hand is controlled using EMG signals from residual muscles. The strategy incorporated in the control of the model is a two muscle “digital” control system. This means that the signals are generated by two antagonistic muscles and that the signal is detected if it reaches an upper threshold. The controls can distinguish between a short and a long contraction of the signals to provide the user with additional control to operate the hand. The controls developed for the prosthesis are not as user friendly as the manual control because it is designed for users with at least some experience using the hand. This control mode only has a few input signals compared to that of the manual control mode which makes it more difficult to produce the same and even higher functionality as is needed for the prosthetic hand. For the prosthetic hand functionality is the most important property to be provided by the control system. The user will have to go through a learning process of how to operate the hand. The signals must be used as physiologically possible to make control more natural and to relief the mental load on the user during operation. If the signals are used naturally, in other words the same control signal that would have been used if the hand was still intact is used to perform the functioning of the prosthesis, it will be easier for the user to learn and use these controls. The best way to use these control signals to control the hand effectively is to have pre-programmed hand shapes[4,20,23]. These hand shapes are based on the most commonly used hand shapes used by the human hand during normal daily operation. Various hand shapes as determined by different researchers as being the main hand shapes were evaluated by the author

(Section 3.5.2.2). Combining this with the authors own theories as well as having the right number of shapes for easy selection of hand shapes lead to the decision to have 9 basic hand shapes:

PRECISION GRIPS(Figure 4-52):

- *Needle:* Grip between tip of the thumb and the index finger, with the other fingers flexed (to pick up small objects)
- *OK:* Grip between the tip of thumb and index finger, with the other fingers extended (to pick up small objects, looking like an OK sign).
- *Chuck:* Grip between tips of the thumb, index and middle finger (used to grasp a pen when writing).
- *Tip:* Grip between the tip of the thumb and the tips of the other fingers (pick up a long thin object).

POWER GRIPS(Figure 4-53):

- *Small cylindrical:* Grip between the four fingers and the palm with the thumb wrapped around the fingers (to grasp small cylindrical object).
- *Large cylindrical:* Grip between the four fingers and the thumb and palm together (to grasp large cylindrical object).
- *Spherical:* The same grip as the large cylindrical grip with fingers abducting (to grasp a spherical object).
- *Side:* Grip between thumb and the side of the flexed index finger, all other fingers flexed (crushing a nut between the thumb and index finger).

LINK(Figure 4-54):

- *Park:* The four fingers almost fully flexed and the thumb at the side of the hand half flexed (relaxed hand position).

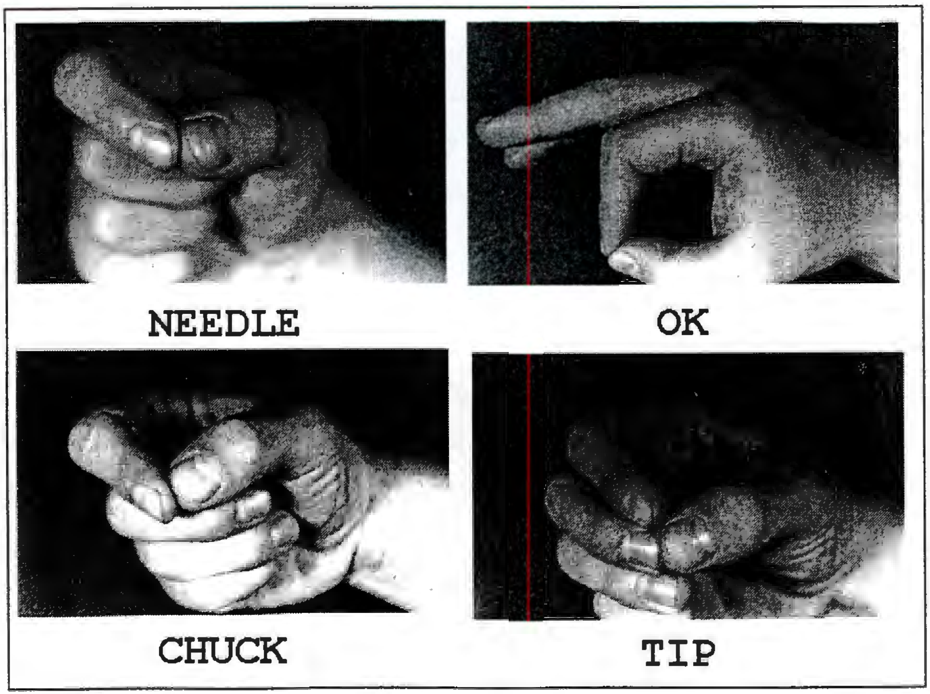
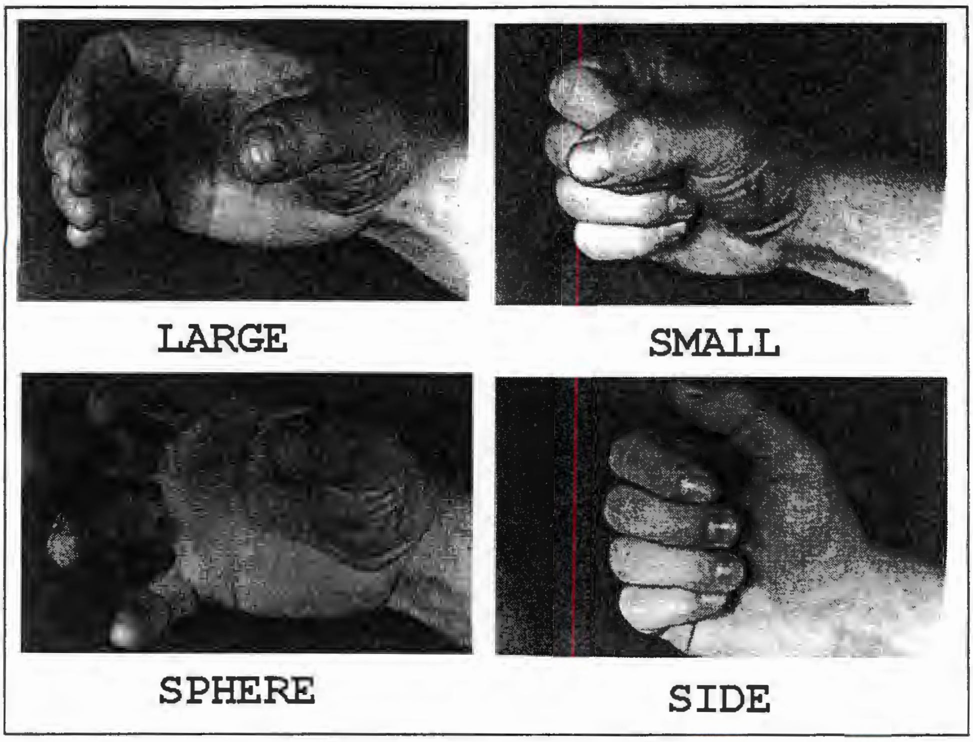


Figure 4-52: The major precision grips of the hand.



LARGE SMALL

SPHERE SIDE

Figure 4-53: The major power grips of the hand.

PARK

Figure 4-54: The link state of the hand.

When the hand is not used it is in the relaxed position waiting for a control signal from the user. The user evaluates the size and the shape of the object to be grasped and decides which hand shape to use. The user then uses combinations of the control signals to select the correct hand shape. The hand changes into the selected hand shape and waits for the user to position the hand so that the object can be grasped in the most effective way. Once in position the user can grasp the object using the control signals. After the object has been manipulated the user can release the object and grasp it again or go back to the resting state of the hand.

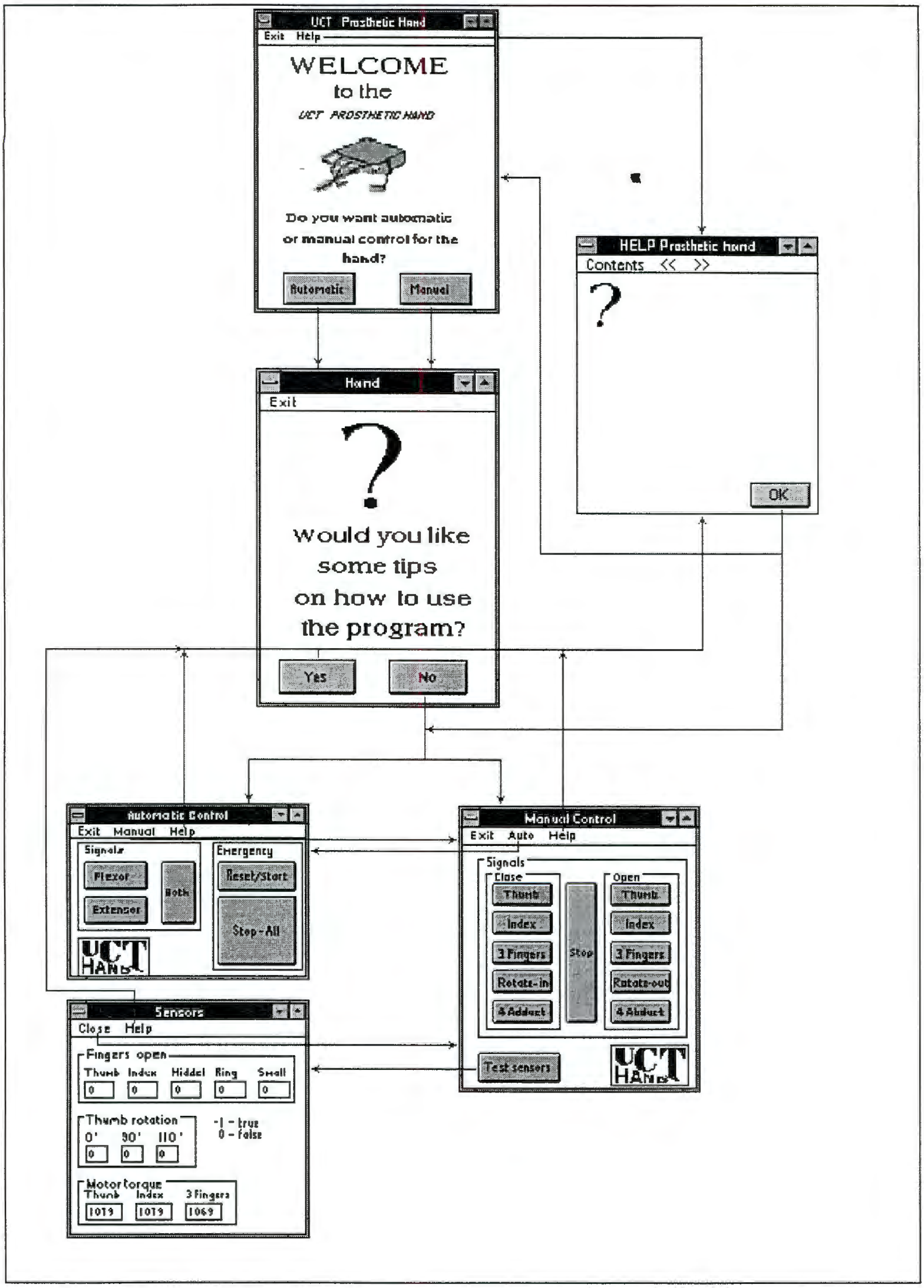
COMPUTER PROGRAM

Chapter 5

The control of the hand is performed by computer software. Visual Basic is an object orientated Widows based program and was chosen for the control of the hand. Visual Basic provides a very user friendly interface through its windows and buttons. The software was available to the author and was supported by the Lego software. Functions and procedures to control the Lego interface box is supplied by the *lego.dll* file and can be used by Visual Basic. An explanation of all the functions and procedures supplied by this file is presented in the *lego.doc* file which is given in Appendix B. The declarations for these functions and procedures are given in the *lego.bas* files which is pasted into the declarations form of the main module of the Visual Basic programme. The relevant computer code for the program is presented in Appendix B. The main program is presented by the *hand.mak* file. This file execute the program since it includes all the other files used in the program but can not be used without the other files. The files to be used in the program can be added or removed from the program by adding or removing the from the file list presented in this file. The file included in the main program all perform different function according to the file extensions. The *hand.bas* file is the main module for the program consisting of all the declarations and subroutines. All the **.frm* files consists of the coding for the separate forms(windows) used when executing the program. These forms contains all the visual information(position, size, colour, fonts etc.) for the form and the commands(buttons, text windows etc.) on the form. It also consist of the declarations and subroutines used by that form only. To provide a good structure for the program, it was written with all the subroutines in the main module(*hand.bas*). The visual information included in the forms are presented later in the chapter while the declarations and subroutines are presented in Appendix B.

To incorporate both of these control strategies the programme was developed to give the user option of controlling the hand like a prosthesis or for educational purposes. This will provide the user with a different control form with the necessary control buttons to operate the specific mode of operation. The program gives the user an option between *AUTOMATIC* operation which gives the prosthetic control and *MANUAL* operation with the control for the children. The flow diagram (Figure 5-1) provides the various windows of the program and shows how they are linked together.

Each window consist of a tool bar and control buttons which can be selected by the user to enable the different functions of the program. In the following section each window is shown in more detail and the functions of the various control objects are explained.


WELCOME

to the

UCT PROSTHETIC HAND

Do you want automatic or manual control for the hand?

Would you like some tips on how to use the program?

Fingers open

Thumb 0

Index 0

Middel 0

Ring 0

Small 0

Thumb rotation

0° 0

90° 0

110° 0

-1 - true

0 - false

Motor torque

Thumb 1019

Index 1019

3 Fingers 1069

Figure 5-1: The main flow diagram for the developed program.

5.1 Control Windows

5.1.1 Welcome window

This is the first window which appears if the interface boxes are connected correctly and switched on, in which case an information box will caution the user. This window welcomes the user to using the program and gives the option of choosing between using the *MANUAL* control or the *AUTOMATIC* control option. This is done by clicking on the *manual* or *automatic* button. Like all the other main windows the first command on the toolbar is the *exit* command which ends the program. The other option is to get *help* before using the program. The contents of the help window is read from a text file, *hand.txt,* which is provided in Appendix B. Exiting the help window will bring the user back to the welcome window. The welcome window is presented in Figure 5-2.

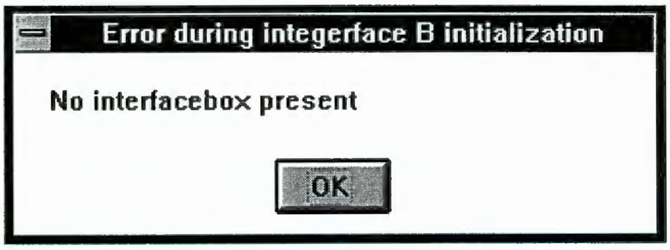
WELCOME
to the
UCT - PROSTHETIC HAND

Do you want automatic or manual control for the hand?

Figure 5-2: The welcome window.

5.1.2 Information window

This window is a standard windows information dialogue box informing the user if the interface boxes are not connected properly or switched on. The program can not function without the interface boxes because it cannot communicate with the motors and sensors. If something is wrong with the Lego interface box the problem has to be solved and the program restarted while if something is wrong with the UCT-hand interface box the user can continue execution providing the problem is corrected. An example of an information box is given by Figure 5-3.



Error during integerface B initialization

No interfacebox present

Figure 5-3: An information box.

5.1.3 More-help window

This window will be switched on when either the manual or automatic buttons on the welcome window are clicked. This window provides the option to obtain further help on how to use the control method which was selected on the welcome window. This is done be selecting the yes or no button. The *No* button will switch on the control window as selected in the welcome window while the *Yes* button will switch to the help window for additional help on the chosen option. Again the *Exit* button on the toolbar will terminate the program. The more-help window is shown in Figure 5-4.

Would you like some tips on how to use the program?

Figure 5-4: The more-help window.

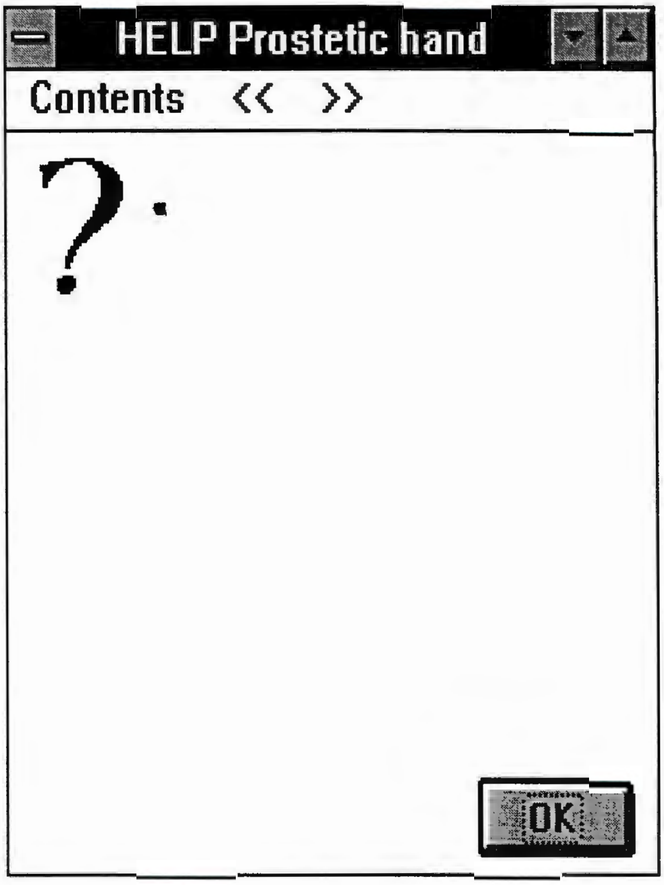


Figure 5-5: The help window.

5.1.4 Help window

The help window provides the user with information on how to use the program. It reads its contents from the *hand.txt* file. The help window is invoked by the Help option on most of the toolbars of the control windows and by selecting the *Yes* button on the more-help window. When the window appears all the other windows are switched off. When invoked the help shown by the window provides information relevant to the active window before the help window appeared. Using the *OK* button will return the program to that same active window except if it was the more-help window in which case the manual or automatic window is switched on depending on the choice made in the welcome window. There are six different help pages for all the windows. While the help window is active the user can select other help pages by using the *Contents* option on the toolbar and selecting a page or by paging forward and backward using the >> and << options. This will not effect the window to which the program returns after using help. The Help window without the text is shown in Figure 5-5.

5.1.5 Manual window

This window provides the user with the controls for the *MANUAL* operation of the hand. Using the buttons the user can control each of the motors in the hand individually. The window consists of two main columns; an *Open* and a *Close* column. Each column has five buttons, one for each motor. The two signals controlling the opposite directions of the motors are provided by adjacent buttons in the opposite column. The five buttons in each column are;

- *Thumb:* flexion/extension of the thumb
- *Index:* flexion/extension of the index finger
- *3-Fingers:* flexion/extension of the last three fingers
- *Rotate-in/out:* rotates the thumb for opposition
- *Abduct/Adduct:* abduct/adduct the four fingers

Between the two columns is a *Stop* button which will stop all the motors running at that stage. Clicking on the *Sensor* button switch on an additional sensor window which presents the values of all the limit switches and force sensors in the hand while operating it in the manual mode. The toolbar provides the user with *Exit* to end the program as well as *Help* on how to use this window and finally the *Automatic* option to switch directly to the automatic window for *AUTOMATIC* control of the hand. The manual window is shown in Figure 5-6.

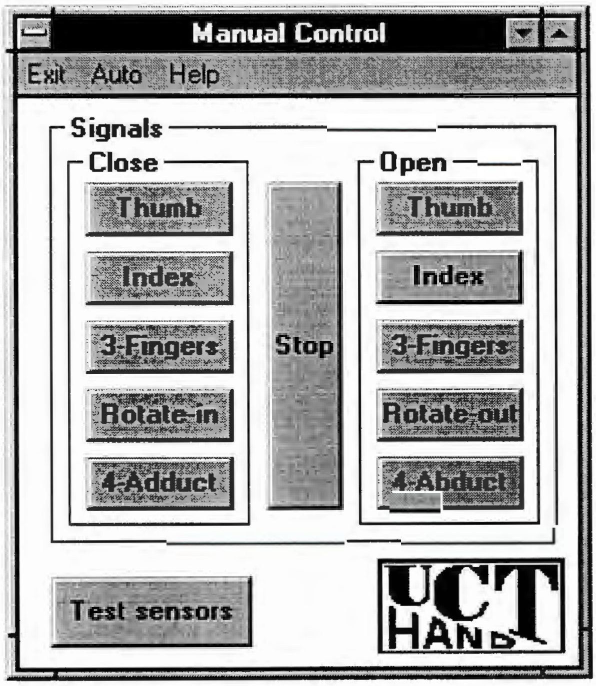


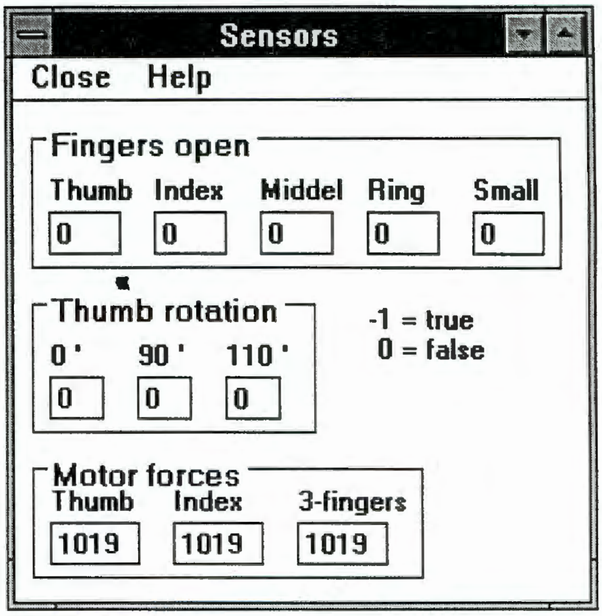
Figure 5-6: The Manual control window.

5.1.6 Sensors window

This window provides the user with information about the sensors in the hand. It can be used to ensure the sensors are working properly or to demonstrate the working of the sensors. The window is switched on by the Sensors button on the manual window. The window appear simultaneously with the manual window. There are three frames displaying the sensor inputs:

- *Fingers open:* full-extension sensor for each finger
- *Thumb rotation:* three angle sensors for thumb rotation
- *Motor forces:* relative forces in the three flexor motors

The sensors detecting the full flexion of the fingers as well as the rotation angle of the thumb are digital sensors and can therefore only be on or off. when the limit switch makes contact the sensors windows shows 0 and when it is close the sensor window shows -1. The *motor forces* frame presents a measurement of the current in each of the flexor motors which is relative representation of the torque in the motor and the force applied by the finger. These sensors only provide useful answers during the closing of the fingers because the interface box can only read positive values. The values can also not be compared to each other but only used to see how it increases as the force in the hand increases and what is the maximum value for each finger. The *Close* object on the toolbar will make the window disappear and switch the manual window back into its normal mode again while the *Help* object will provide help on how to interpret the sensor window. Figure 5-7 shows the sensor window.



Fingers open

Thumb: 0
Index: 0
Middel: 0
Ring: 0
Small: 0

Thumb rotation

0 ': 0
90 ': 0
110 ': 0

-1 = true
0 = false

Motor forces

Thumb: 1019
Index: 1019
3-fingers: 1019

Figure 5-7: The sensors window.

5.1.7 Automatic window

This window provides the user with the necessary signals for the *AUTOMATIC* control of the hand. The objects are the same as the signals that would be found in a real prosthetic hand. The are two main frames; *Signals* represent the EMG signals which would be provided by the users residual limb and *Emergency* which represent the buttons which would switch the hand on or reset the hand or switch all the motors off if something goes wrong.

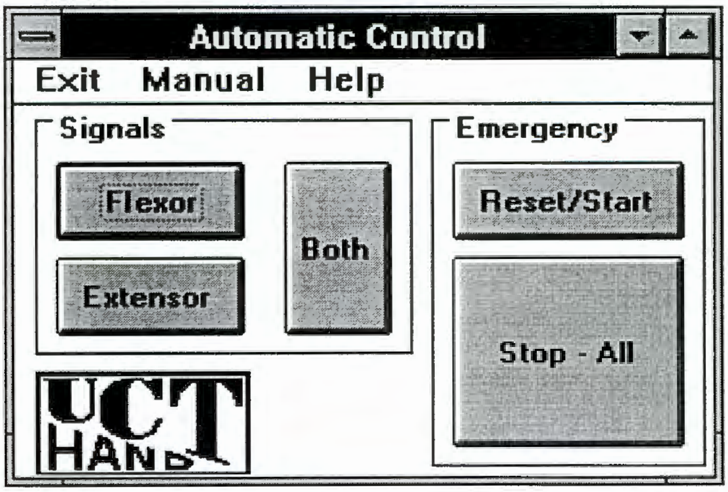


Figure 5-8: The automatic control window.

The *Flexor* and *Extensor* button represents the EMG signal from the flexor and extensor muscles while the *Both* button represents both the muscles contracting at the same time. The buttons can either be "clicked" representing a short muscle contraction or "held down" for half a second representing a long muscle contraction. This provides the user with a combination of six signals to control all the movements of the hand. The *Reset/Start* button is used to start the operation of the hand or to reset the hand at any time. This will move the hand into the parked mode and switch on the dialogue window which will continually guide the user through the steps. In the real prosthetic hand the sequence of events will have to be remembered by the user but to make it easier for the user of the program the dialogue window is provided. The *Stop-All* button provide an emergency switch to switch all the motors off if something goes wrong. The *Exit* option on the toolbar again terminates the program with the *Help* option providing help on the automatic window. To switch to the manual window the *Manual* option from the tool bar can be used. This can be done at any time and can be used to correct any mistakes that might occur during the automatic operation of the hand. The automatic is shown in Figure 5-8.

5.1.8 Dialogue window

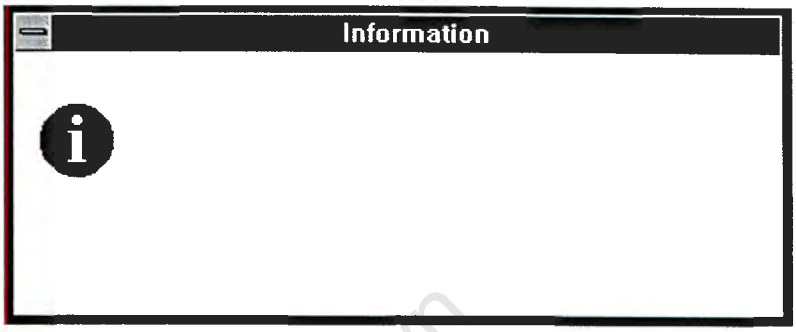


Figure 5-9: The dialogue window.

The dialogue box looks like the information window but does not have an OK button. The window is automatically invoked by the programme while using the automatic window. The contents of the dialogue window guides the user through the steps that should be taken at each stage during automatic operation of the hand. The window has no objects and is a read only window changing its dialogue to assist the user. The window shows the user the available options to choose from using the three signals in the automatic window. To differentiate between a “click” and a “hold down” of a button the window presents the first in small letters (“both”) and the latter in capital letters (“BOTH”). The dialogue window without any contents is presented in Figure 5-9.

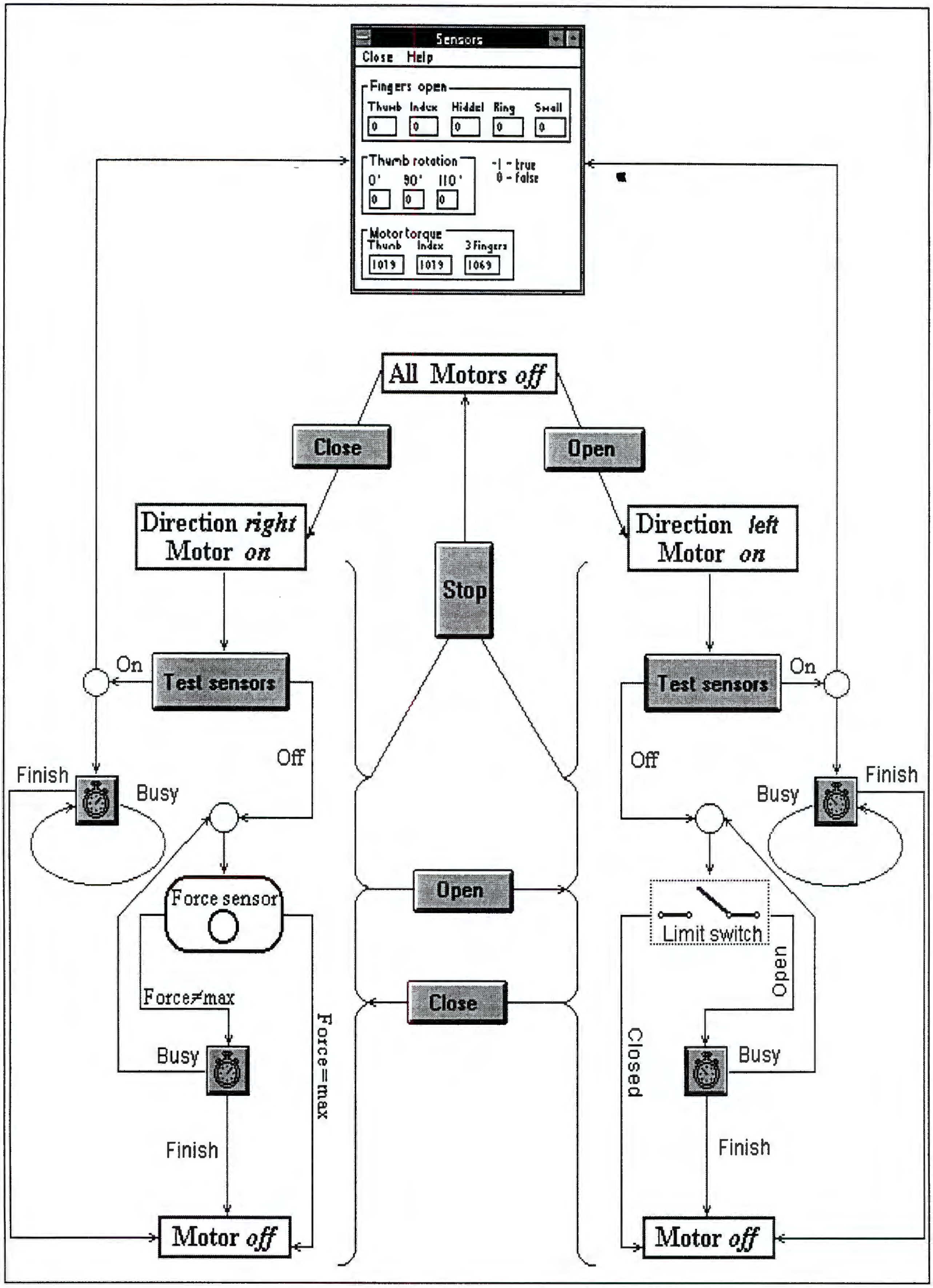
5.2 Control algorithms

5.2.1 Manual Control

The manual control of the hand is designed to be used mainly by children. The control must be simple and provide the user with as much control over the hand as possible. To achieve this the user is provided with control over the individual motors of the hand. Keeping the average user in mind the hands control must be fitted with safety mechanisms which will make sure the controls of the hand does not get mixed up or that the motors in the hand are not damaged. There are five motors in the hand controlling all the movements. Each of these motors is controlled individually in both directions which means two control signals is needed for each motor.

When the motors deliver high torque a very high current is drawn which causes permanent damage and reduces motor life. When full flexion of the fingers are reached or the stops in the fingers are reached the motor responsible for that finger will stall. The first method of prevention is to switch the motors on for a time slightly longer than the full closing time of the finger to ensure the motor is not switched on indefinitely. Another way to prevent stalling by monitoring the current in the flexor motors as well as switching the motors off when a limit is reached. For the rotation limits in the thumb the limit switches detect when the 0 degree or the 110 degree limit is reached, and the rotation motor is switched off. When the fingers are extended there is no mechanical way from preventing the tendons to start winding in the opposite direction after full flexion is reached. This reverses the flexion/extension motion of the finger and inverts the functions of the control buttons which is very confusing and will disrupt the automatic operation of the hand totally if not corrected. To prevent this from happening each finger is fitted with an extension limit switch at the MP joint to detect when each finger is fully extended. When full extension is reached in a finger the corresponding motor is switched off. The motor flexing the last three fingers is switched off when the first finger reaches the extension limit. A Stop button is provided by the active window which overrides all the other commands and will stop all the running motors at once

An additional use of the manual control strategy for the hand is to use it to correct any errors which could occur while using the automatic control. This might happen as a result of faulty limit sensors or force sensors or control boxes not switched on. If at any stage during automatic operation of the hand things are not working the way they are supposed to the best way to determine the problem is to switch to the manual window. After switching to the manual window the direction of the motor actuation should be checked first. If directions of the motor actuation is co-ordinated with the directions indicated by the buttons it is an indication of faulty limit sensors. To check this which sensors do not work properly the *sensors* button is used to switch on the sensors form which contains the signals from all the sensors during manual operation. By manually extending the fingers to there extension limits and rotating the thumb through its full range the sensors can be tested to see if they work. While the sensors are switched on the control of the hand changes slightly. The protection given by the sensors to stop the motors during normal manual operation is ignored since the purpose of this mode is to drive the fingers to the limits and test for the proper working of the sensors. During the operation of the fingers in this mode the program is constantly monitoring all the sensors. While in the mode caution should be taken not to let the motors stall or invert their motion. A close contact between the limit switches are shown as a -1 and an open contact as a 0. If the limit switches do not detect closure when they are supposed to the contact areas might be dirty or in the case of the extensor sensors the MP joint might be clamped too stiff, preventing the torsional spring from closing the switch properly. Loosening the joint and cleaning the contact area from time to time should secure smooth operation of the hand. The flow diagram for this manual operation of the hand is shown in Figure 5-10.



Sensors

Close Help

Fingers open
Thumb	Index	Middel	Ring	Small
0	0	0	0	0

Thumb rotation
0°	90°	110°
0	0	0

-1 - true
0 - false

Motor torque
Thumb	Index	3 Fingers
1019	1019	1069

Figure 5-10: The flow diagram presenting the manual control of the hand.

Automatic control

The automatic control of the hand is the same as the control of a real prosthetic hand. The signals that would have been provided by the EMG from the user's residual muscles are provided by control buttons on the active window of the program. The hand uses only three buttons to control all its major functions except to reset the hand or switch it on or off. To make the hand truly functional using only these three signals requires a controlling scheme which should be learnt by the user. The control should still be as natural as possible to relieve the mental load on the user. The EMG signals of the hand are represented by three control buttons on the automatic window. The Flexor button represents the signal from the flexor muscle and the Extensor the signal from the extensor muscle while the Both button represents the simultaneous contraction of the two muscles. To use these buttons in the same way as for the prosthetic hand it can be "clicked" which represents a short muscle contraction or "held down" which represents a long muscle contraction. A timer is set on the buttons to determine how long it is been pushed down and the time limit set at half a second for a "held down". When any button is used and indicator is set to a specific constant value which is used as the control signal to trigger branching in the program. The indicator is the same as the instructions given by the dialogue window and the same notation will be used to explain the programme:

- *flex:* Flexor button clicked
- *FLEX:* Flexor button held down
- *extensor:* Extensor button clicked
- *EXTENSOR:* Extensor button held down
- *both:* Both button clicked
- *BOTH:* Both button held down

All the functions of the hand must therefore be controlled using only six input signals. The most physiologic and functional way to control the hand is to have a lower level of control for the hand. The lower level control is performed by software and can not be altered by the user. It consists pre-programmed functions and algorithms developed by the designer of the hand. In the case of the developed model the lower level control is used to form selected hand shapes, to grasp and release the object and to return to the resting state. The lower control is responsible for the direct control of the individual actuators with the correct timing and speed to perform the desired function together with the other actuators. The lower control uses input from the sensors on the hand when necessary to perform certain functions. The higher level control of the hand is provided by the user using combinations of the six input signals. The signals are used to activate the desired lower level functions. Before an object can be grasped the user uses visual feedback to evaluate the size and shape of the object and decides which one of the hand shapes he wants to use to grasp the object. The shape is selected and the hand changes to form this shape up to the point where it is ready to be correctly positioned with respect to the object to ensure the best grip. When the user is satisfied with the positioning of the hand the object can be gripped. After gripping the object can be released on command of the user.

The selection of the specific hand shapes have been discussed in Section 4.10.2.2. The author determined 9 main hand shapes which are essential for proper functioning of the hand. These shapes can be selected by the user and are divided as follows:

- *PRECISION:* needle, OK
  chuck, tip
- *POWER:* small and large cylindrical
  spherical, side
- *NEUTRAL:* park

The PARK shape is similar to the relaxed hand shape of the human hand when it is not used and is used as a reference hand shape since it can be carefully set to be exactly the same every time. From the PARK shape any other shape can be formed with ease. Thus, whenever the hand is switched on or reset or when the user wants to re-select a hand shape the hand returns to the PARK shape. This leaves the user with 8 hand shapes to choose from. To make it easy for the user they are divided naturally as POWER and PRECISION grips. These groups are subdivided into pairs that fit together as indicated above. The user first selects either a power or a precision grip and the similar pairs are selected using similar buttons with the one clicking the button and the other keeping the button down. At any stage during operation there is a point where the user can go back and start the selection process all over again.

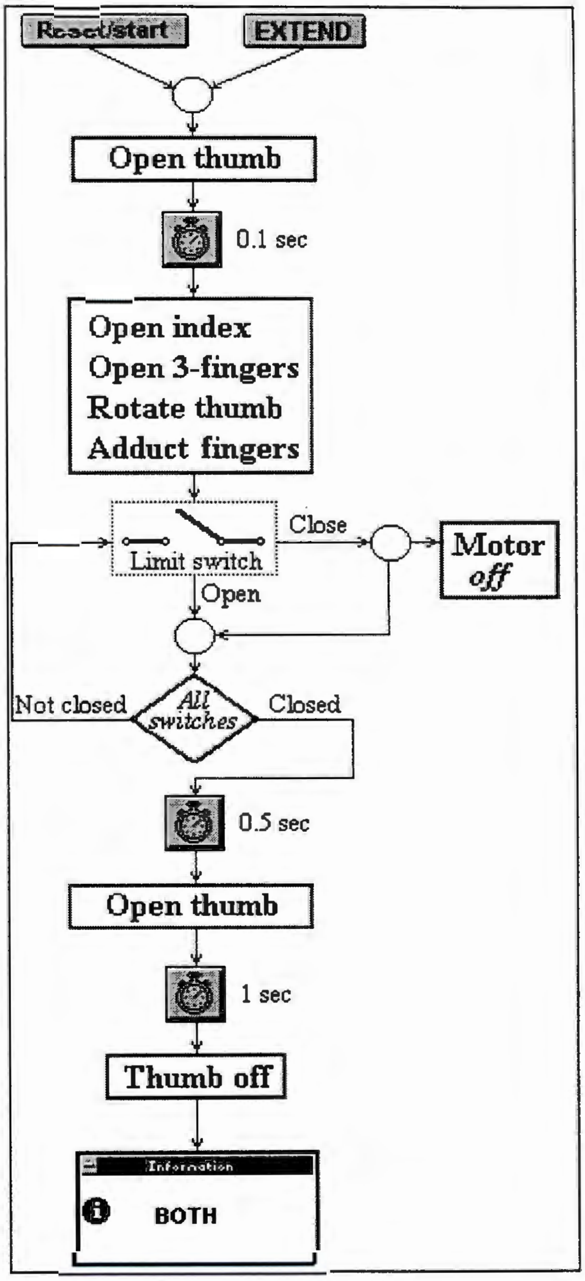


Figure 5-11: Flow diagram explaining how the park hand shape is achieved.

Forming the right hand shape is achieved because the positions of all the fingers is known when the hand is parked. To achieve the parked hand shape while the hand is in any position can only be done by first moving the fingers to a position where their position can be detected by the sensors after which the parked shape the can be formed. The motors can be switched on for a certain time which will ensure that they end in the same position every time. To prevent interference between the thumb and the other fingers the thumb is opened first because it should always be on the outside of the other fingers though it is not essential. The index finger follows shortly after the thumb and then the other three fingers followed by the outward rotation of the thumb as well as the adduction of the four fingers. These movements occurs simultaneously while the limit sensors are monitored. When any of the fingers reach the full extension limit that finger is switch off or in case of the three fingers if one of them reach its limit. The thumb rotation is stopped when the thumb is in the 0 degree position beside the hand. The hand will wait until all the motors have been switched off before it flexes the thumb for a second to give the hand a more natural shape. The flow diagram explaining the control to park the hand is provided by Figure 5-11.

The ideal is to have the signals being used physiologically as they are used during the selection process.

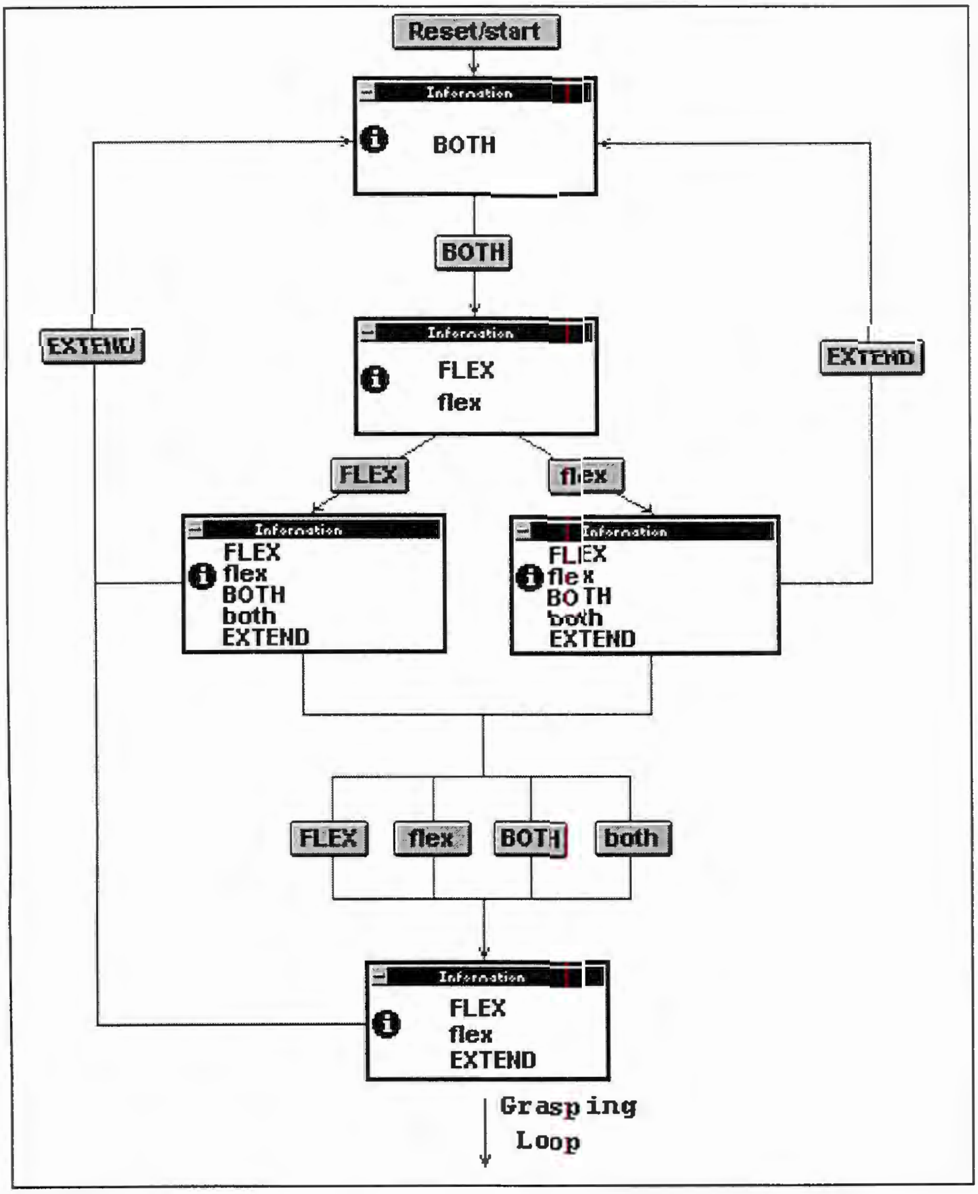


Figure 5-12: The flow diagram presenting the automatic control of the hand to the point where the hand is ready for closure.

In other words using flexing signals when the user with a normal hand would have used flexor muscles. This is unfortunately not always possible but the author tried to keep the control as natural as possible. The *both/BOTH* signals are always used for selection purposes and not for grasping while the *flexor/FLEXOR* signals are used mainly for movement involving closure of the hand and during the final hand shape selection. For the hand shape selection the *both* and *flexor* signals are used for the shape in the pair which needs the least closure from the parked position while *BOTH* and *FLEXOR* signals are used to select the shape which require the largest closure. The *extensor/EXTENSOR* are used mainly for opening the hand and for re-selecting hand shapes or resetting the hand. The flow diagram for the control of the hand up to the point where the hand shape is formed is shown in Figure 5-12 and the software performing the function is done by the subroutine *Park_Grip* in Appendix B.

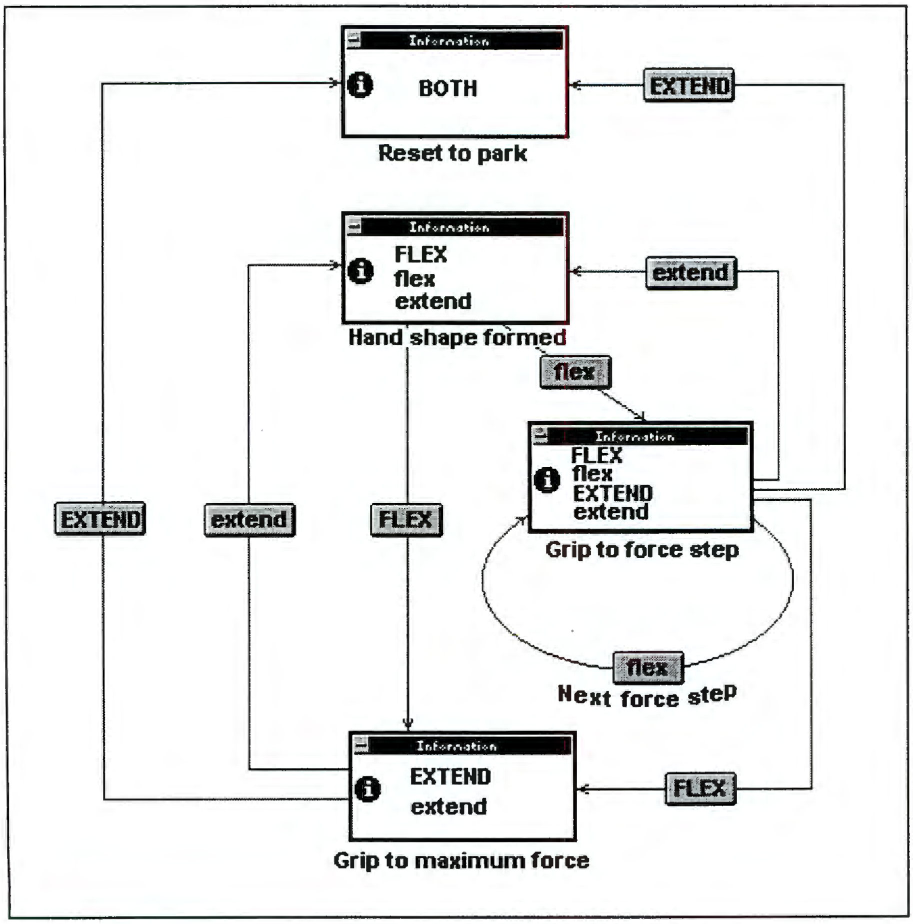


Figure 5-13: The flow diagram presenting the grasping of the hand.

When the hand shape is formed the hand waits for the signal to either close the hand or reset the hand to the PARKED shape. To ensure the hand can grip soft objects without breaking it as well as having a strong grip on a hard object the hand can be closed in different force steps. Each of the flexor motors are connected to a current sensor which monitor the current drawn by the motor and thus the relative force in the finger or fingers in case of the third motor (Motor C). A low force level which is enough to grip an object softly as well as a maximum level which is slightly lower than the highest level the motor can reach and three additional force values between the two extremes are selected for each finger. When the *flex* option is chosen the first time the hand grips the object according to the specific grip with each finger gripping until the force inside the finger reaches the minimum value. Using the *FLEX* option will flex the fingers until the maximum force in each finger is reached. While the hand is gripping the object to the minimum force it waits for a signal from the user. The user can use the *flex* signal again which will flex the hand until the next force step in each finger is reached. This can be done for the all the force steps until for the last step the force will be the maximum force for all the fingers or at any step the user can use the *FLEX* signal to go directly to the final force step. Similarly, using the *extend* signal will release the grip on the object and go back to the point where the current hand shape was just formed while using the *EXTEND* signal will reset the hand back to the parked shape. The flow diagram to explain the grasping of the object is presented in Figure 5-13.

The only difference between the programming for the different hand shapes is the timing of the motors to form the hand shape and which motors are involved in forming the shape as well as the gripping of the object. The computer code for each hand shape is given under the subroutine with the same name (S*hape_Grip*) in the *hand.bas* file presented in Appendix B.

TESTS AND RESULTS

Chapter 6

The hand was designed with its primary function being to be used for the further development of a multi-fingered prosthetic hand and its secondary function to be used as an educational tool. The concept model was built to develop basic principles and mechanisms which can be used in the design of the real hand and to determine the problem areas. The model was developed successfully and satisfy the demands imposed on it. Exposing the hand to stringent force, speed or grip tests will have no real use because the hand is a concept model and will never perform any where near that of previous developed hands. Simple tests were performed on the hand to provide the author some insight of the possible performance of the prototype if it was developed. The real test for the success of the model is the proper function of all the mechanisms showing full potential to be developed further into the prototype. It is very important that the hand is able to form the desired hand shapes effectively to perform a proper grip on the object using the available control scheme. The effective control of the computer program and ease with which the user can interact with the program is of equal importance.

6.1 Hand shapes

For the hand to perform effectively it needs to apply a firm grip on the object. This grip depends highly on the ability of the hand to adapt to the shape of the object. A large gripping force applied at the wrong point can lead to a poor grip on the object. In the developed hand the effectiveness of the grip depends on the effective formation of the hand shapes. The hand shapes are chosen by the user according to the shape of the object to be gripped. The different hand shapes of the hand were tested using specially shaped objects for each hand shape. The hand was then tested grasping irregular shaped objects. Multiple tests were performed on the grasping of the various objects without any problems. The resulting figures for each of the tests are shown and comments are made on these results for each hand shape.

6.1.1 The Needle shape

This forms a grip between tip of the thumb and the index finger, with all the other fingers flexed, to pick up small objects(Figure 6-1).The shape is performed successfully but due to the design medium the final grip does not allow the user to grip objects which are too small. The thumb and the index finger tips are not positioned at exactly the same location for every trial because there are no angle sensors to measure the exact angle of the finger. The positioning is done be the timing of the motor and the fingers therefore have a slight positioning tolerance. This tolerance however is sufficient for the use of the hand as a model The shape performed by the human hand is a very fine movement, as the name states it is supposed to eventually be able to pick up a needle. When the thumb is placed in the hand the closing trajectory of the thumb should be used and may be adapted to ensure the correct placing for the fingers to meet. Another slight problem is that when high forces are applied on the two fingers the index finger tends to apply most of the force towards the hand instead of perpendicular to the object towards the thumb. This is a function of the design of the finger which is good for power grips but not for precision grips. Since high forces are not normally used in precision grips the grip force is sufficient.

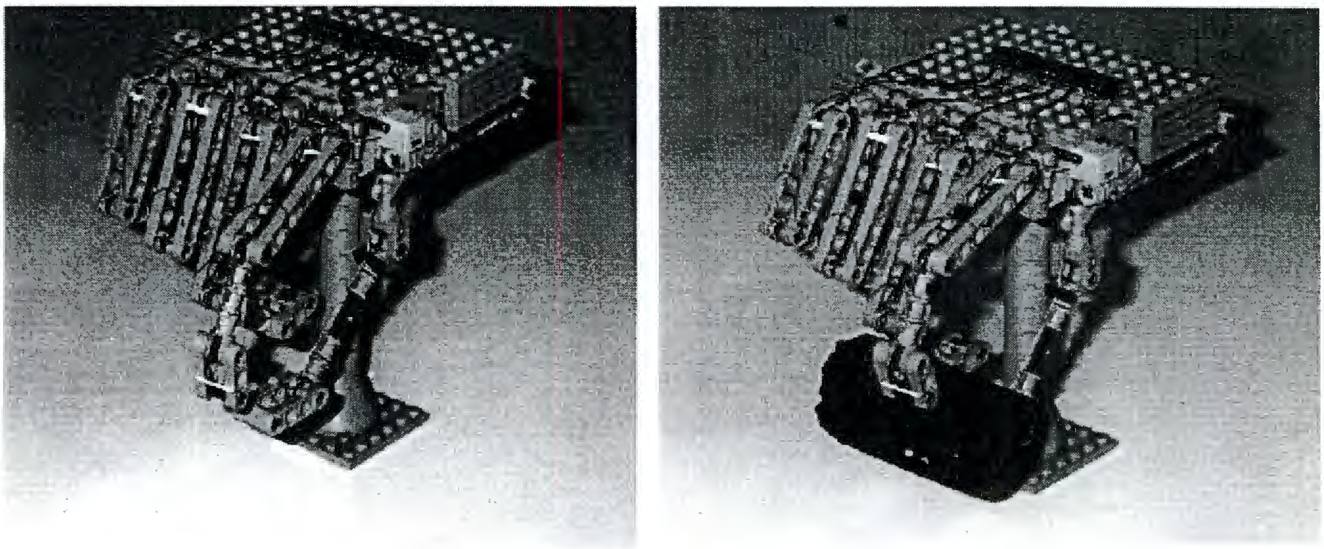


Figure 6-1: The Needle hand shape performed by the hand.

6.1.2 The OK shape

The grip is between the tip of thumb and the index finger, with the other fingers extended, to pick up small objects. The shape looks like "OK" sign used frequently by humans(Figure 6-2).

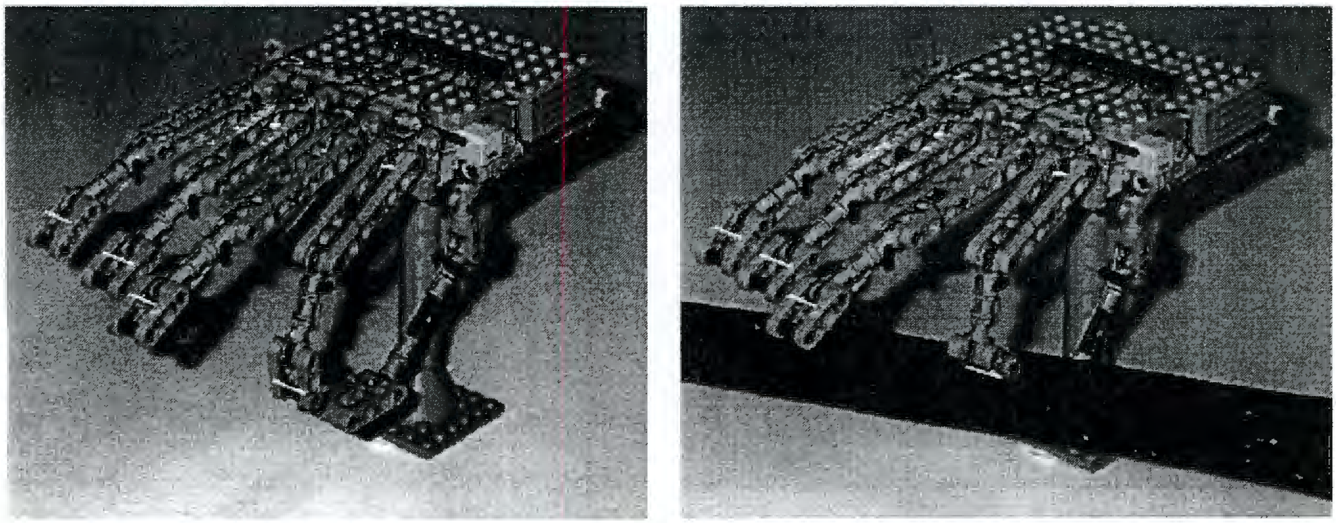


Figure 6-2: The OK hand shape performed by the hand.

This hand shape is similar to the of the Needle shape except for the three fingers which are extended to get them out of the way of the objects depending on the object shape. The test done for the two shapes produced similar results.

6.1.3 The Chuck hand shape

This shape provides grip between tips of the thumb, index and middle finger as used to grasp a pen when writing (Figure 6-3). It is fairly difficult to achieve a proper “chuck” with the low tolerances of the model and the square shape of the finger tips. The shape is fundamentally the same as the needle grip but the three fingers are not flexed all the way to position the middle finger so that it can provide the third jaw of the three jaw chuck form with the thumb and index finger. The tip of the thumb is square and therefore does not provide a solid three chuck grip with the object but more of a two chuck grip between the thumb and the index finger. This can easily be corrected in a real design by the more soft cosmetic covering the would be around the main structure or by twisting the flexion plane of the thumb posteriorly. Getting all three fingers to meet on the right location as with the human hand is very complicated since the grasping trajectory for thumb and index finger during the needle and the chuck grip are not exactly the same. The trajectory for the finger was designed for the needle grip and can not be altered during grasping. The difference is that the thumb and the index finger meet closer to the palm of the hand during the chuck grip to provide a stronger grip with the shorter moment arms to the finger tip. This is achieved by a smaller flexion of the MP joint and larger flexion of the IP joints. The difference is not that significant and will just mean the final design will not have such a strong chuck grip compared to the real hand.

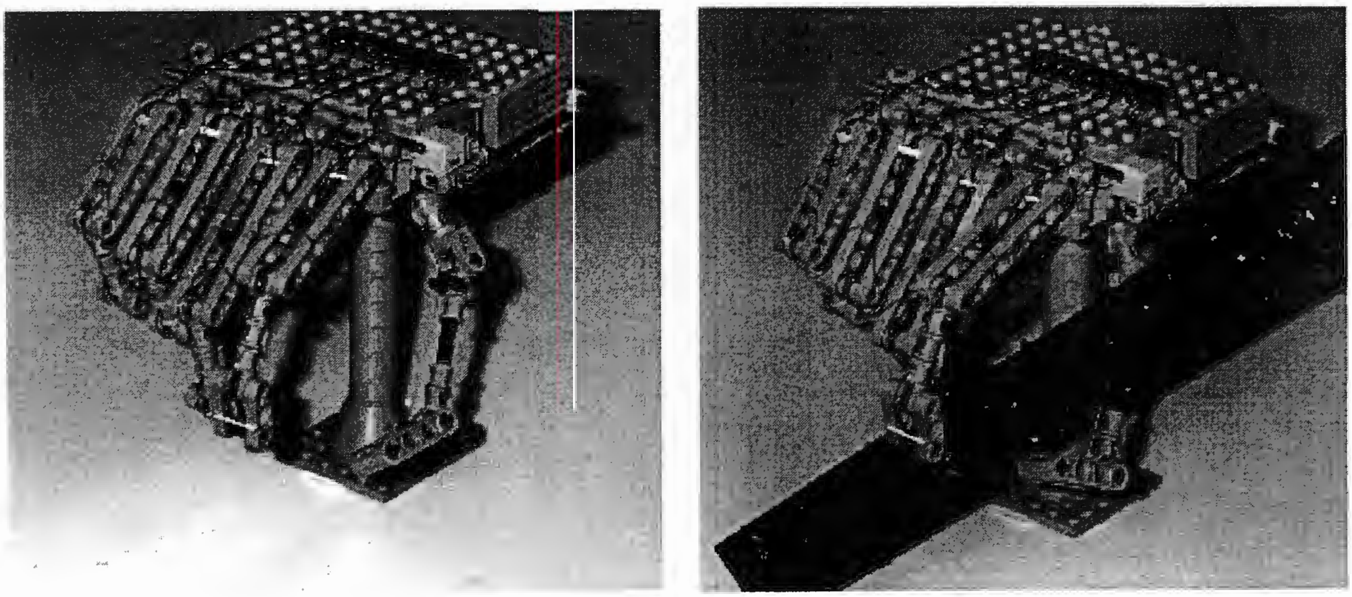


Figure 6-3: The Chuck hand shape performed by the hand.

6.1.4 The Tip hand shape

This grip is between the tip of the thumb and the tips of all the other fingers to pick up long thin objects (Figure 6-4). The tip grip is performed fairly well with only one slight limitation. Interference can be caused between adjacent fingers because the low tolerances provide some degree of play in the abduction/adduction motion of the fingers. To avoid this interference the fingers were designed to adduct leaving enough clearance is between the fingers to avoid interference. This leads to less stable tip grip because the four fingers do not form a solid unit. In the real design with much higher tolerances this should not be a problem. The fingers will also have a smooth surface which would make them less prone to interference allowing a design with less clearance between the adjacent fingers.

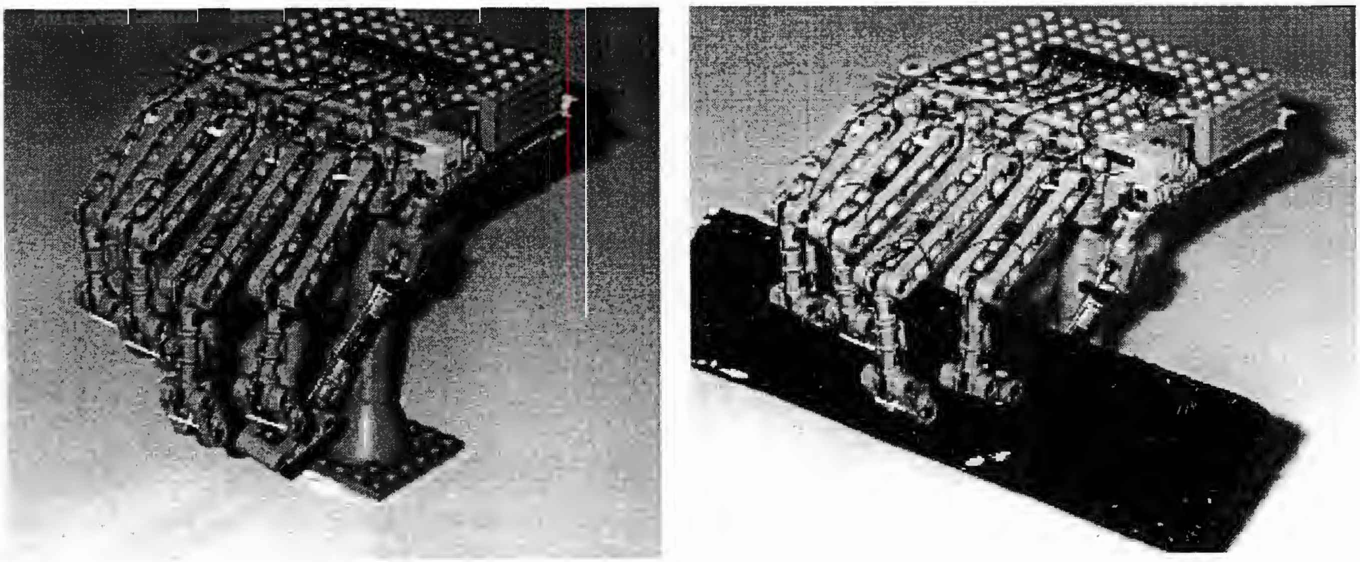


Figure 6-4: The Tip hand shape performed by the hand.

6.1.5 The Small cylindrical hand shape

This forms a grip between the four fingers, the palm and the thumb. The fingers clamp the object against the palm while the thumb is wrapped around the fingers for additional stability and grip force to grasp small cylindrical objects. The combination of all these result in one of the hand's` strongest and most often used grips. In addition to gripping small objects the hand can be used in its opened state as the "hook" function which has been described by several researchers as a very useful hand shape. This can be described as the hand shape used to carry a suitcase. The small grip has a very good performance providing a very stable and strong grip on the object. The model can not grasp cylindrical objects with very small radii. When fully flexed the space inside the grip, between the thumb and other fingers, does not close off totally like in the real hand. This is mainly due to the absence of the soft cosmetic layer which provides additional volume in the inside of the fingers to fill this space and to deform around the object. The thumb wrapping around the other fingers provide a very tight grip on the object.

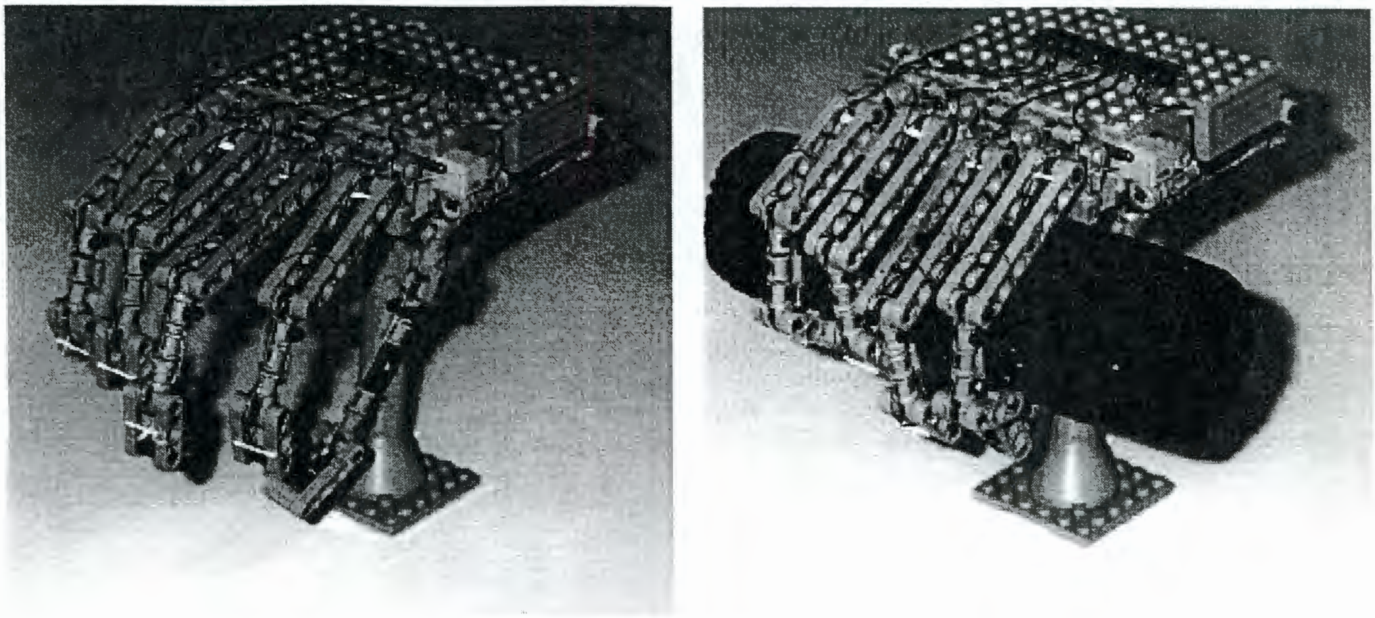


Figure 6-5: The Small cylindrical hand shape performed by the hand.

6.1.6 The Large cylindrical hand shape

This shape forms a grip between the four fingers and a combination of the thumb and the palm to grasp large cylindrical objects (Figure 6-6). The large grip has the best performance of all the grips providing a very stable grasp on the object. This is largely because the hand was designed primarily for grasping of hand sized irregular shaped objects which is used most commonly by the human hand. The size of the object fits the trajectory of the finger perfectly and the fingers have a smaller internal elasticity to overcome because of the less torsioned joint springs.

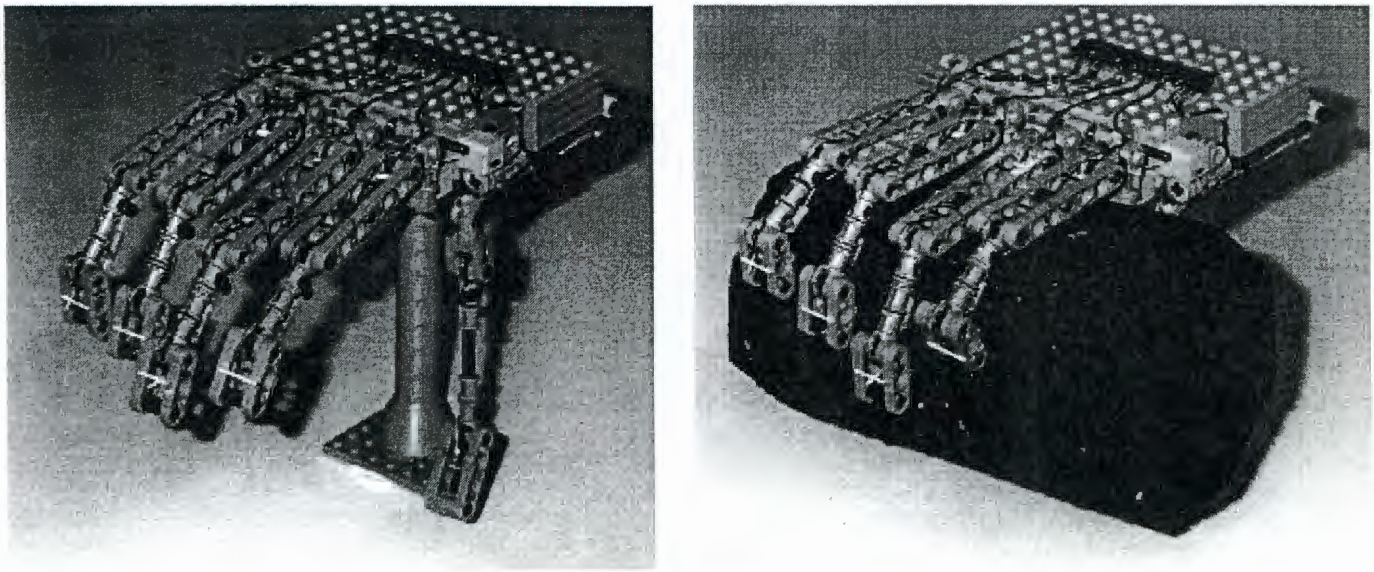


Figure 6-6: The Large hand shape performed by the hand.

6.1.7 The Spherical hand shape

The hand shape provides the same grip as the large cylindrical grip with the four fingers abducting to have a wider grasp which is distributed more towards the side of the spherical object (Figure 6-7). The spherical grip provides a very stable grip on the object. As with the small grip the spherical grip can not grasp small objects. The Lego enforce the placing of parts and members perpendicularly, in line or equally spaced with other members. This constricts the design of the parts of the hand to be square compared to the more irregular shape of the human hand which provides better grip. In the design of the real prosthesis members can have irregular shapes which would overcome this problem.

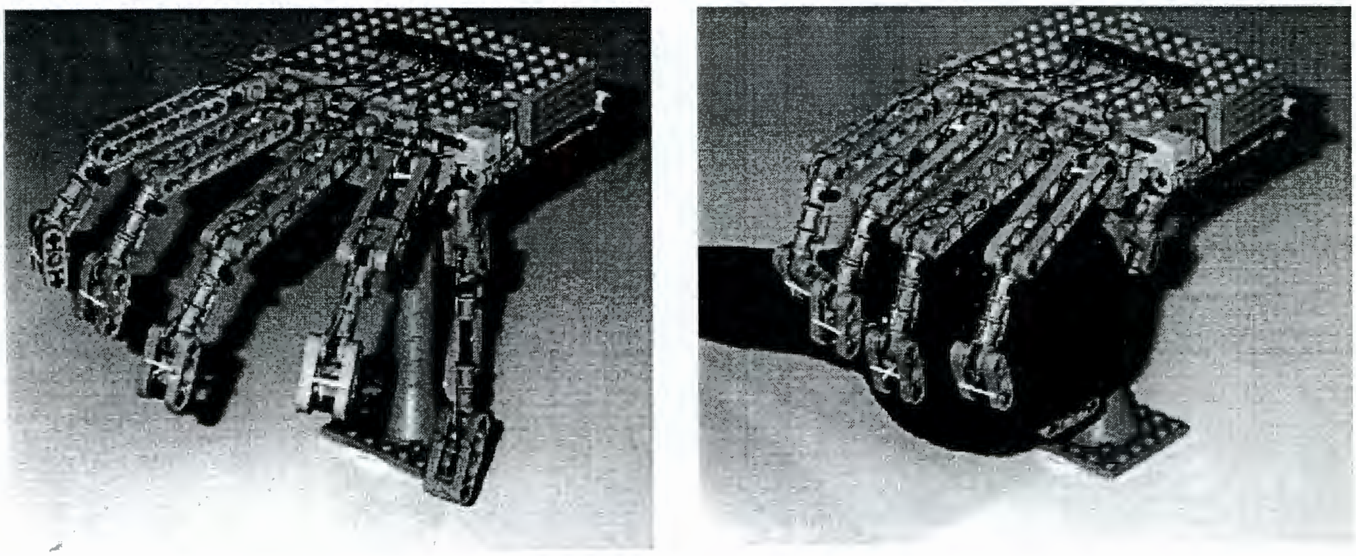


Figure 6-7: The Spherical hand shape performed by the hand.

6.1.8 The Side hand shape

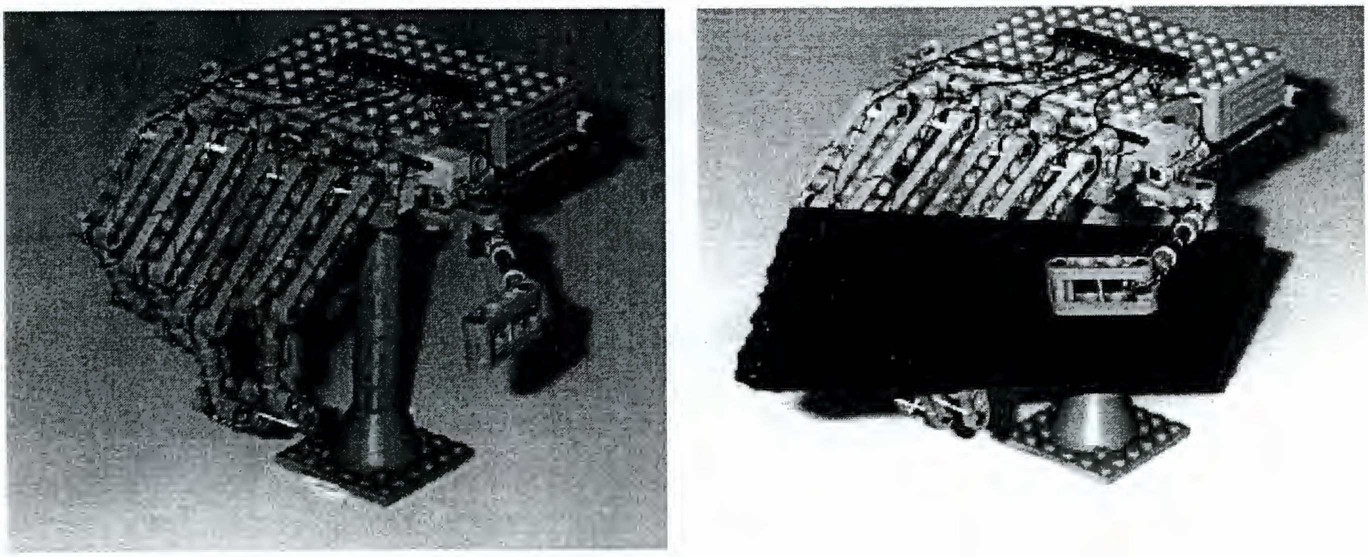


Figure 6-8: The Side hand shape performed by the hand.

This grip is between thumb and the side of the flexed index finger with all the other fingers flexed as if crushing a nut between the thumb and index finger (Figure 6-8). Due to its simplicity the side grip provides a very easy grip to achieve. The only problem with the grip is the play in the MP joints of the fingers. The thumb grips the object against the side of the index finger which gives way slightly and affects the stability of the grip. This will again not be a problem in the real hand since the tolerances on the joints will be much higher.

6.1.9 Park

The four fingers almost fully flexed with the thumb at the side of the hand half flexed like the relaxed hand position(Figure 6-9).

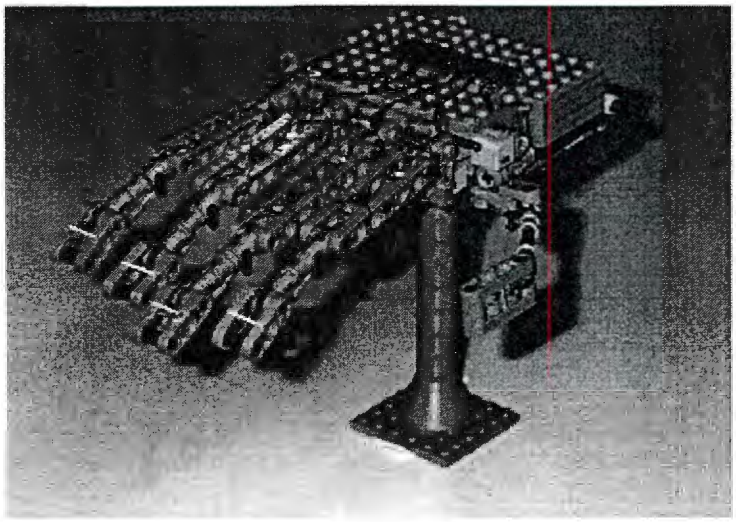


Figure 6-9: The Park link mode for the hand.

This grip is not a functional grip as such but can be used as a support underneath any object. The major purpose of the mode is to provide a reference shape for the other hand shapes to be formed from. The shape of the hand during the park mode should therefore always be the same. The shape also represents the hands natural shape when it is relaxed and not being used. The test for the functionality for this mode is therefore to determine if the hand returns to the same position every time and that this can be achieved with the hand being in any shape. The hand returns to the park mode successfully from any of the prescribed hand shapes but does give some problems when the thumb was flexed inside the other flexed fingers. The park mode was designed to be formed from all positions providing the thumb is outside the other fingers since this is more natural to occur. The algorithm is written so that the thumb starts opening 0.1 second before the other finger to avoid interference, but if the thumb is on the inside it will interfere with the fingers

6.1.10 Irregular shapes

The hand was tested on various objects of which the shape and surfaces were made randomly and proved to grip all of them effectively (Figure 6-10).

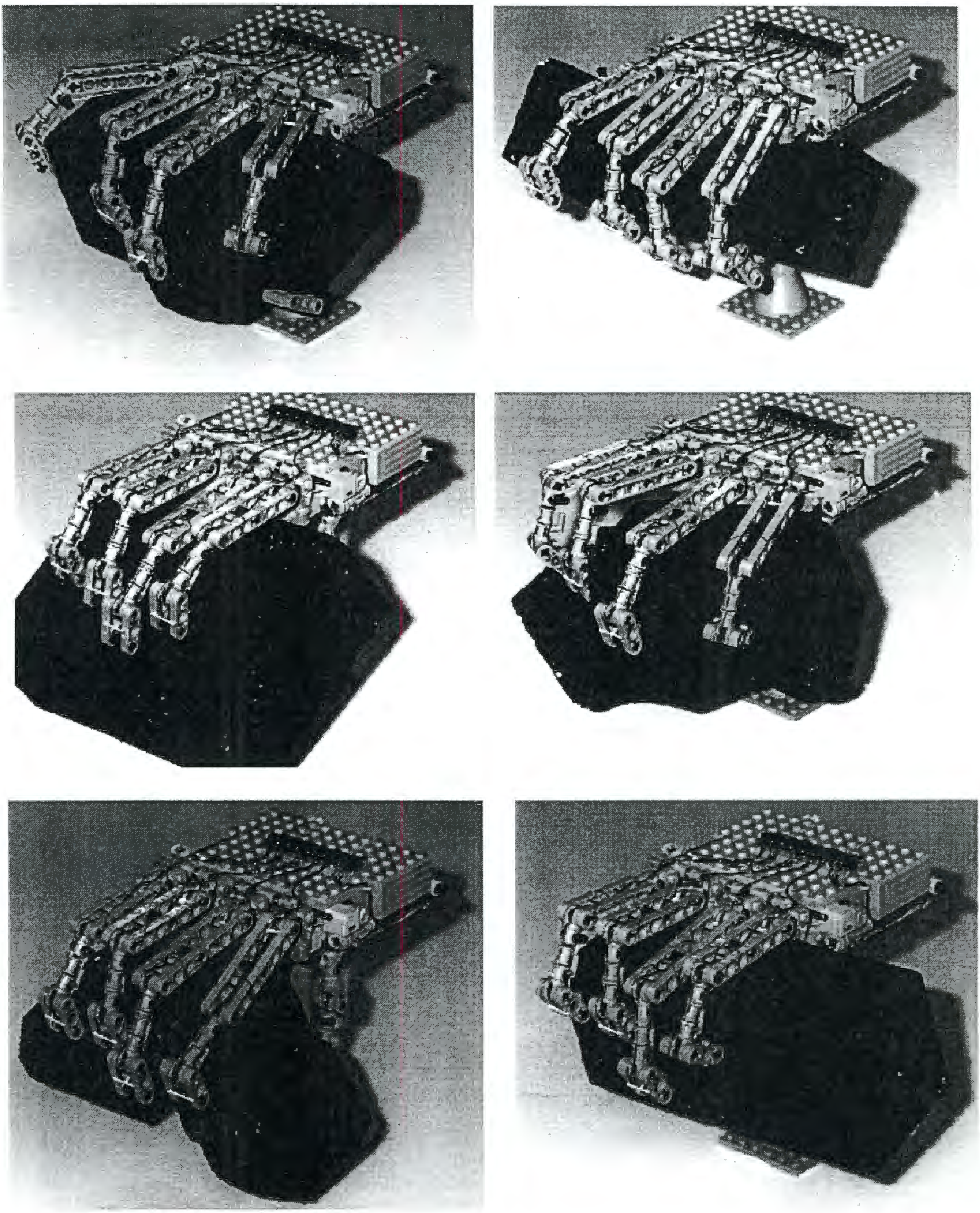


Figure 6-10: Grasps performed by the hand on irregular shaped objects.

If the correct hand shape for the specific object is chosen by the user the adaptability of the hand allows it to accommodate for the irregular shape of the object. The hand is not very strong but can grip basically any shaped object if it is not too heavy.

6.2 Performance Tests

Since the hand was designed as a concept model and with Lego as a medium it can not be expected to perform anything close to a real prosthetic hand or even more ambitious, the human hand. A few very basic tests were performed to provide a means of comparison. All the measurements and calculations are shown in Appendix A.

6.2.1 Grip size

The *maximum* and *minimum* grip size of the hand was measured. This is important to know because it provides the limitations for the size of the object which can be gripped successfully by the hand. The maximum grip size was taken as the opening width of the hand during the forming of the large grip while the minimum size was taken as the diameter of the space inside the hand as it is fully flexed in the small grip. These sizes are scaled down by 1:1.2 to be compared to the real hand and other prosthetic hands.

6.2.2 Finger speed

The shape of the finger changes constantly during the closing trajectory making it difficult to get absolute values for the speeds. The speeds for the flexion of the finger were taken as the average *angular velocity* of the MP joint and as the *average tip speed* during the whole motion. To determine the average angular velocity the deflection angle at maximum flexion was measured and divided by the time duration for the finger to close to this point. The tip speed was determined by drawing the actual trajectory of the finger during flexion and measuring the distance travelled and dividing the distance by the time taken for this flexion. The *rotational angular velocity* of the thumb was set by the author in the software to ensure not to be too high to ensure good detection of rotation angles by the angular sensors. The time for the thumb to rotate from the 0 degree position to the 110 degree position was measured and divided into the 110 degrees to get the average angular velocity.

6.2.3 Grasping forces

Grasping forces are difficult to determine because it acts in different directions and have different sizes at different locations on the finger trajectory. Since the fingers are adaptable the forces change according to the surface of the object. There are two types of forces of interest to compare the performance of the hand. The first is the *pinch force* between the tip of the thumb and the index finger during the precision grips and the second is the maximum total *grip force* exerted on an object during the power grips. The grip force it not equal to the sum of the pinch forces of all the fingers since the contact area and the force directions are very different during the power and the precision grips. The forces were determined using the system shown in Figure 6-11. It consists of a water filled balloon of which the outlet is connected to a vertical tube. The balloon is gripped by the hand and the rise in pressure due to the force applied by the hand causes the water level in the tube to rise. The system is calibrated applying known forces and recording the equivalent rise in the water level. This system provides a easy way of determining the total force applied on the object.

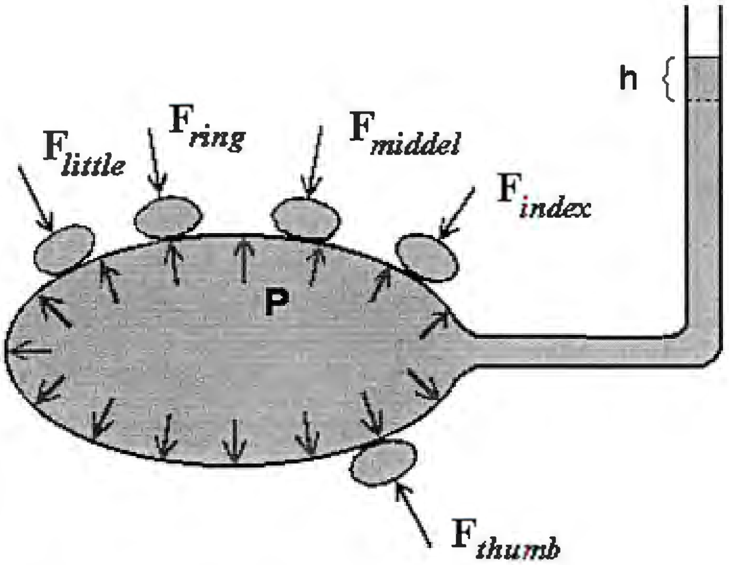


Figure 6-11: Apparatus for measuring the grasping forces in the hand.

6.2.4 Results

The results of all the test performed on the hand are tabulated in Table 6-1.

Performance Task		**Value**
Grip size:	maximum	75 mm
	minimum	25mm
Finger speed:	flexion angular velocity	15.48 °/sec
	flexion fingertip speed	27.15 mm/sec
	thumb rotation angular velocity	51.40 °/sec
Grasping force:	pinch force	1.04 N
	grip force	2.60 N

Table 6-1: The results for the performance tests on the model.

6.3 User Interfacing

One of the most important tests for the hand was to fulfil its secondary function which is to be used as and educational tool. The two parts of the program are evaluated individually since they were developed for different types of users.

6.3.1 Manual operation

The manual operating mode is developed for use by less experienced users and children or to manually correct errors that might occur during the automatic operation of the hand. Operation of the hand in the manual mode is very easy since it provides individual control over the motors in the hand. The safety features built into the hand protects the hand from abuse or wrongful use by children. The sensors window enabling the user to detect and correct errors in the hand by providing the user with the values of the individual sensors. The help files which can be activated in every window guides the user by explaining how to operate the hand and what all the controls on each window are used for. The manual operation for the hand provides a good medium for explaining the basic operation of the hand and distribution of the motor functions.

6.3.2 Automatic operation

The automatic operation of the hand is developed for more experienced users, particularly users with knowledge of prosthetic control devices. The operation mode provide the user with a control of the hand typical to the control of a real multi-fingered prosthesis. The user control all the gripping functions of the hand using various combinations of two signals. During operation the information window provides all the available options at any stage of the operation. The sequence of the signals to achieve the different functions of the hand are developed to be highly physiological and therefore easy be learnt by the user. The experienced user can easily operate the hand without the help of the information windows. For the less experienced users the help files which can be activated at any time provide the necessary explanations on how to operate the hand. The hand presents users with an interesting tool to explain the working of a real prosthetic hand. The automatic operation mode of the hand provides a good medium for explaining the control of a multi-fingered prosthetic hand.

RECOMMENDATIONS AND CONCLUSIONS

Chapter 7

7.1 Recommendations

Further development of the hand can be done for both applications it was designed for. The fundamental difference between these two applications will inevitably lead to a stage where the individual application will have to be developed separately. Developing the hand as an educational tool means making it more interesting to the users by adding more features to it. This is the opposite of what is desired from the prosthetic hand. Developing a real prosthetic hand will mean producing a real robust prosthetic hand with the least additional features as possible to make the hand as practical as possible. It is proposed that any further development of the hand in either of these directions is done separately to ensure the most functional system for the specific purpose.

7.1.1 Further developing of the Lego model

Running the hand with *Visual Basic 4* on a faster computer should improve the reliability and the precision of the hand shapes of the hand. Contrary to Visual Basic 3.1, Visual Basic 4 support binary numbers. The inputs from the parallel ports are easier in their binary form because each bit represents a port pin which is true (1) or false (0). In the present program the input had to be converted into a binary string which slows down the running time for each loop. The faster the loop the quicker the sampling rate of the ports which leads to more accurate detecting of the limit switches.

A project which would be very interesting, is to fit the hand with various *force and slip sensors.* The developed hand was designed to be a prosthetic hand and for that purpose the development of sophisticated sensors was impractical but this could be a very interesting project and lead to a more interesting hand to use for the educational purposes.

Another very similar project to the hand could be to develop a controllable *Lego arm* to fit on the hand. This would also provide a more interesting display of the hand which will definitely capture the imagination of young children.

A more electrical development that can be attempted to make the hand more interesting is to develop a system that can detect *EMG signals.* This can easily be incorporated in the software to replace the existing control signals. Using the real EMG signals to control the hand and maybe have visual displays of the signals while operating the hand could be highly educational to children for understanding the human body and prosthesis. Replacing the computer control of the hand with a *programmable computer* *chip* ("E-Prom") at the same time will produce a mobile prosthetic hand which does not need a personal computer to be controlled.

Enabling the children to *program* the hand themselves would make the hand very interesting and educational to use. Unfortunately programming the hand in Visual Basic is not that easy and would be too complicated for most children. The software has to communicate to the external environment through the computer ports which involve "low" level programming. Developing an object orientated user interface which automatically does the lower level programming for the children. The child should be able to program the hand by selecting different objects in various time sequences.

7.1.2 Developing a prototype

The hand proved to very functional and effective but changes should be made if it is to be developed further into a real multi-fingered prosthetic hand. The final design will depend highly on the available technology and components. The restrictions on the hand are set by the human hand which it is supposed to replace are very strict forcing optimal use of space and having an almost custom made design for the available components. A few recommendations are made to consider in the development of the real prosthetic hand.

Contrary to prosthetic hands the forces exerted by the fingers in the concept model is not very high. Very high forces might lead to heavily deformed finger grasping trajectories. A thorough *study of the finger under various loading conditions* especially the precision grips are necessary to ensure that the actual force is applied in the right direction. When performing the precision grips the final gripping forces are applied in the direction of the palm instead of normal to the object. This is favourable for the power grips where the object is gripped including using the palm but not for the precision grips where it is gripped between the tips of the fingers. In the prototype it would also be easier to incorporate mechanisms like the dorsal expansor of the human hand in the concept model (Section 2.3). These mechanisms exist to change the action of the forces as the grasping trajectory changes. By lack of a stronger optimisation package the author could only optimise the finger system to find the trajectory but if a stronger package is available the whole trajectory with all the variables influencing them can be optimised to find the solution for the finger mechanism providing the optimal functionality.

If the present feedback is not sufficient to control the hand efficiently touch and other *sensors* can easily be incorporated in the design. This depends highly on the technology available to the designer. Small angle sensors that could be built into the joints could be beneficial to the control if it does not lead to additional circuitry.

The prosthetic hand will have to be made much *more cosmetic*. The present dimensions are scaled up by 1:1.2 because of the dimensions and attachments of the Lego but the real prosthetic hand will have to be built at full scale. The hand will also have to be covered with a soft outer layer over which the cosmetic glove can fit to provide the cosmetic feel. The latter is commercially available and subsequently not incorporated in the design of the hand. To ensure the outer layer and the glove do not effect the motion of the hand due to additional resistance and space, it should be attempted to incorporate them into the design method. Changing the dimensions of the hand to be more like the real hand will improve cosmesis as well the function of the hand. Placing the MP joints on a slight three dimensional arc as in the hand instead of straight lines will improve the grip on spherical objects considerably. Changing the rotation axis of the thumb to a more optimal plane will improve the effectivity of the grip provided by the thumb.

In the design of the model the motors used were square and the most accessible and stable position for the motors was with the driving axes towards the outside of the palm. In the prototype though the motors can be fitted in any stable position allowing the *motors to be turned around* to be closer to their actuation points. Spaces can be left between the motors to conceal some of the driving mechanisms like the abduction shaft.

If there is enough space in the design of the hand to incorporate the *Crowder's linkage bar or small differentials*[4] these mechanisms can be considered for use in the hand since they could not be incorporated in the model due the specific restrictions imposed through the design medium.

There is no mechanical way in the model to *prevent the fingers from winding in the wrong direction* because of the lack of space and the absence of small enough devices. This is prevented by the extensor sensors only but if they become faulty the whole co-ordination of the hand is out of control and can not be corrected using the prosthetic control signals. In the model the manual part of the software can be used to correct such a mistake but this is not available in the prototype. Such a mechanical device should be built into the hand or a connection should be available which could override the prosthetic control signals and correct the mistake.

If it is possible the *circuitry* of the prototype should be designed in such a way that the Hall sensors are not needed. Their function in the model is to detect the motor currents using a separate power supply. This was necessary because of the restrictions of the Lego interface box which was not designed for this purpose. With the prototype all the circuitry will be custom designed for the specific purpose to drive the hand, making it easier to avoid using Hall-detectors. In the prototype the circuitry will also be driven by batteries resulting in a different circuitry. Additional space in the prototype should be left to incorporate the circuitry and the batteries since they are not fitted into the design of the model. The batteries can be fitted into the forearm or the wrist or somewhere on the body if it is impossible to fit them into the hand itself.

To improve the needle and OK grips of the hand a *pincher* can be developed like that of "Otto Bock".[3] The pincher provides more accurate grip for the grasping of very small objects.

7.2 Conclusions

A concept model for a multi-fingered prosthetic hand was developed using Lego as a design tool and medium to build the model. The hand was designed for two primary functions; the first and most important was to serve as a concept model for further development into a practical prosthetic hand and the second was to serve as an educational tool to stimulate children's interest in the engineering field. Software was developed to control the hand through a personal computer. The software was also developed to accommodate the different types of users expected to use the hand and was developed in such a way that it allows a user with no knowledge of prostheses to operate the hand.

The hand was tested by the author performing numerous trials. All the trials were performed successfully and the performance of the hand were found to be satisfactory. The hand proved to be very promising and provides a good foundation for the further development of a multi-fingered prosthetic hand. The mechanisms developed are very practical and robust and can be incorporated in future designs. The controls of the hand are easy to use due to the easy to operate windows based control software and the logical application of the control signals. As expected, the hands speed and force performance could not really be compared to that of the human hand or other prosthetic hands. This is because it was not intended to be the most important design criteria for the hand considering that the hand was developed to be a concept model to test control theories and mechanisms. What was of much importance was the performing of the various principles and their functionality for further development. The tests performed on the hand showed that the principles are very practical and highly functional. All the movements and hand shapes are formed without any difficulty. From hand shape tests it is clear that the power grips are performed better than the precision grips. This is mainly due to the play in the fingers joints which make the precision grips more unstable. To perform the ideal precision grip a different finger trajectory is needed than that used for the power grips.[10] For cosmetic purposes the finger trajectory was designed to close with a wider trajectory than is wanted for the precision grips. The human hand has more control over individual joints to ensure the most efficient grip or to manipulate the object to perform a better grip which can not be done with a prosthetic hand. It also clear that the hand does not perform very well for picking up or grasping small objects. This is a result of the low tolerances of the hand and the absence of soft cosmetic covering which provide additional, better shaped and more adaptable gripping surface. By using the right materials, high tolerance manufacturing and high quality industrial components with a slightly altered design to incorporate the different shaped components, the short comings of the present model can be rectified and a very functional and robust multi-fingered hand can be developed using the principles in this concept model. The hand performs sufficiently to be used as an educational toy but for further development interesting projects can be launched to give the hand additional interesting features.

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APPENDIX A

TESTS AND CALCULATIONS

A.1 Motor toque tests

The torque is measured by winding a mass, m, hanging on the end of a string onto the shaft of the motor. The force, F, applied by the mass is given by:

$$F = m \cdot g \qquad (A\text{-}1)$$

where: g = gravitation (9.81 m·s^2)

The torque, *T*, on a shaft with a radius of *r* is given by:

$$T = F \cdot r \qquad (A\text{-}2)$$

To determine the toque versus speed relation for the motor the rotational speed of the motor has to be determined. The speed of the motor shaft is too high for the Lego rotational sensors to measure directly. This was overcome by counting the number of rotations after the test was done and not during the test. The motor is switched on for a time interval, *t*, from a starting point. The string is then unwind from the shaft until the initial position for the mass is reached and the revolutions, N_{rot}, counted. The rotational speed ϖ of the motor is given as:

$$\varpi = N_{rot} / t \qquad (A\text{-}3)$$

The torque is multiplied and the rotational speed divided by the gearbox ratio to determine the theoretical output of the gearbox for comparison with the real output. The results of the test are presented in Table A-1.

Mass (g)	Torque (N·mm)		Rotational speed (r.p.m.)	
	Measured	Theoretical	Measured	Theoretical
0	0	0	45.2	0.70625
53	0.779895	49.91328	42.2	0.659375
106	1.55979	99.82656	31.8	0.496875
159	2.339685	149.73984	20.3	0.3171875
212	3.11958	199.65312	14.65	0.22890625
240	3.5316	226.0224	9.98	0.1559375
252	3.70818	237.32352	0	0

Table A-1: The torque measured at the motor shaft and the theoretical prediction of the torque at the output shaft of the gearbox..

The rotational speed at the end of the gearbox is low enough to measure directly while the torque test are performed. The motor is switched on for a time interval and the revolutions counting during this period. The results are given in Table A-2.

Mass (g)	**Torque** (N·mm)	**Rotational speed** (r.p.m.)
0	0	0.66
53	0.779895	0.6
106	1.55979	0.56
159	2.339685	0.5
212	3.11958	0.46
265	3.899475	0.44
318	4.67937	0.38
371	5.459265	0.32
424	6.23916	0.32
477	7.019055	0.26
530	7.79895	0.22
583	8.578845	0.2
636	9.35874	0.16
689	10.138635	0.18
742	10.91853	0.14
795	11.698425	0.1
848	12.47832	0.1
901	13.258215	0.1

Table A-2: Data for toque measured at gearbox output.

The efficiency, η, of the system is given by:

$$\eta = \frac{\text{Measured gearbox torque}}{\text{Theoretical gearbox torque}} \cdot 100 \qquad (A\text{-}4)$$

$$= \frac{13.258}{237.32} \cdot 100$$

$$= 5.6\ \%$$

The available torque at the bear box shaft had to be divided by three to determine the available torque to each of the three fingers which had to be driven by the same motor. The force applied at each finger can therefore be determined as:

$$F_{finger} = \frac{T_{gear\ box} / 3}{r_{pully}} \qquad (A\text{-}5)$$

$$= \frac{13.258 / 3}{4}$$

$$= 1.05 \text{ N}$$

A.2 Analytical formulation

The force F which causes the moment M_i for the free body diagram.

$$\tan\alpha_i = \left[\frac{r_i \sin(\psi_i) - r_{i+1}\sin(\beta_i)}{l_i + r_{i+1}\cos(\psi_i) - r_{i+1}\cos(\beta_i)}\right]$$

$$= \left[\frac{r_i \sin(\beta_{i-1} + \theta_i) - r_{i+1}\sin(\beta_i)}{l_i + r_{i+1}\cos(\beta_{i-1} - \theta_i) - r_{i+1}\cos(\beta_i)}\right]$$

$$\alpha_i = \arctan\left[\frac{r_i \sin(\beta_{i-1} + \theta_i) - r_{i+1}\sin(\beta_i)}{l_i + r_{i+1}\cos(\beta_{i-1} - \theta_i) - r_{i+1}\cos(\beta_i)}\right] \qquad (A\text{-}6)$$

Moment balance at each joint:

$$M_i = f(F, \theta_i, \beta_i, \beta_{i-1}, r_i, r_{i-1})$$

$$= F\{\cos\alpha_i (r_{i+1}\sin\beta_{i+1}) + \sin\alpha_i (l_i - r_{i+1}\cos\beta_{i+1})\} \qquad (A\text{-}7)$$

A.3 Final formulations for the basic finger

The moment equation at each joint yields:

$$M_1 = F\{\cos(\alpha_1)(r_2 \sin\beta_2) + \sin\alpha_1 (l_1 - r_2\cos\beta_2)\}$$

$$M_2 = F\{\cos(\alpha_2)(r_3 \sin\beta_3) + \sin\alpha_2 (l_2 - r_3\cos\beta_3)\}$$

$$M_3 = F\{\cos(\alpha_3)(r_5 \sin\beta_5) + \sin\alpha_3 (l_3 - r_5\cos\beta_5)\}$$

with:

$$\alpha_1 = \arctan\left[\frac{r_1 \sin(\beta_2 + \theta_1) - r_2\sin(\beta_1)}{l_1 + r_2\cos(\beta_2 - \theta_1) - r_2\cos(\beta_1)}\right]$$

$$\alpha_2 = \arctan\left[\frac{r_2 \sin(\beta_3 + \theta_2) - r_3\sin(\beta_2)}{l_2 + r_3\cos(\beta_3 - \theta_2) - r_3\cos(\beta_2)}\right]$$

$$\alpha_3 = \arctan\left[\frac{r_4 \sin(\beta_5 + \theta_4) - r_5\sin(\beta_4)}{l_3 + r_5\cos(\beta_5 - \theta_4) - r_5\cos(\beta_4)}\right]$$

The deformation energy is given by:

$$U_{Tot} = \tfrac{1}{2}(K_1\theta_1^2 + K_2\theta_2^2 + K_3\theta_3^2)$$

The moment at each joint can also be written as:

$$M_1 = K_1\theta_1$$

$$M_2 = K_2\theta_2$$

$$M_3 = K_3\theta_3$$

Boundary conditions for each joint is:

$$0 \le \theta_1 \le 90°$$

$$0 \le \theta_2 \le 90°$$

$$0 \le \theta_3 \le 90°$$

A.4 Determining the spring constant

Steel wire with a 0.4 mm diameter was wound twice to produce an inner diameter of 6 mm to fit comfortably but not too loose over the joint axis. This spring was subjected to a moment to determine the spring constant, k.

$$k = \frac{M}{\Phi} = \frac{F \cdot r}{\Phi} \qquad (A\text{-}8)$$

$$= \frac{(0.6)(0.024)}{\pi / 2}$$

$$= 0.00915 \ \text{N/rad}$$

The relationship between the number of turns an the spring constant is given by:

$$N = \frac{d^4 E}{64 D k} \qquad (A\text{-}9)$$

The reduced equation is given by:

$$N = \frac{C}{k} \qquad (A\text{-}10)$$

The constant, *C,* is constant for a spring with the same wire diameter, inner diameter and made from the same material. Equation 4-6 can thus be rewritten as:

$$N_2 = \frac{N_1 \cdot k_1}{k_2} \qquad (A\text{-}11)$$

$$= \frac{(2)(0.00915)}{0.00915} \approx 2 \ \text{windings}$$

A.5 Final finger dimensions

The final finger dimension for the developed hand are presented in Table A-3 and Figure A-1.

Dimensions (mm)	Fingers				
	Thumb	Index	Middle	Ring	Little
l_1	57	47	56	47	40
l_2	24	34	35	34	34
l_3	-	16	16	16	16
r_1	22	10	10	10	10
r_2	49	25	26	25	25
r_3	26	11	11	11	11
r_r	-	9	9	9	9
β_1	17°	36°	36°	36	36
β_2	8°	11°	11°	11°	11°
β_3	15°	40°	40°	40°	40°
β_4	-	22°	22°	22°	22°

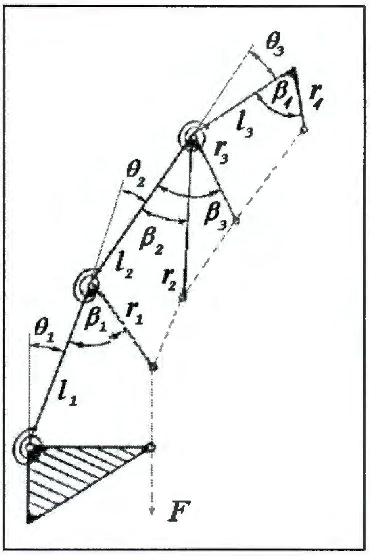

Table A-3 and Figure A-1: The final finger dimensions.

A.6 Current vs. Torque tests

Mass (g)	Torque (N·mm)	Current (analogue)
0	0	94.185
28	0.27468	274.43
53	0.51993	277.21
106	1.03986	280.26
159	1.55979	333.905
212	2.07972	349.63
∝	∝	405.735

Table A-4: The torque and current measurements.

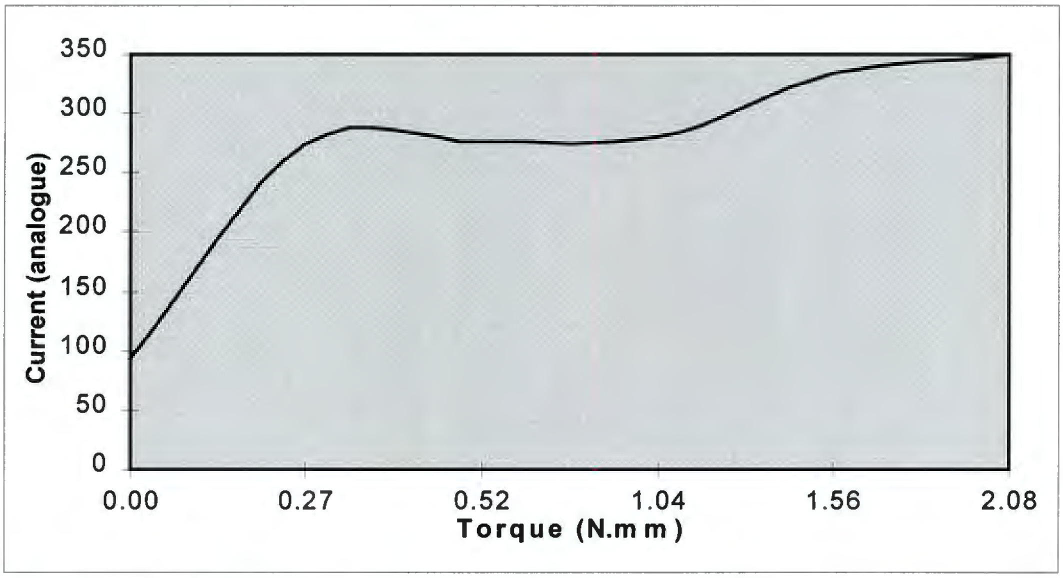

Figure A-2: Current vs. Torque measurements of a motor.

The torque measurements were done as described earlier in Section A.1. The radius of the drum connected to the motor output shaft is 1mm. The current value measured by the hall detectors and is presented as an analogue value by the software. The measured data is given in Table A-4 and is plotted in Figure A-1.

A.7 Grasp tests

A.7.1 Grip size

The largest grip size is achieved while the hand is performing the large cylindrical grip. The largest hand opening is measured from the tip of thumb to the tip of the index finger as 90mm. The smallest object that can be grasped using one of the power grips is gripped using the small cylindrical grip. The diameter of the object is measured as 30mm. Converting these values by a scale of 1:1.2 to be compared to full scaled hand yields:

$$\textit{Full scale dimensions} = \textit{Measured dimensions} / 1.2 \qquad (A\text{-}12)$$

A.7.2 Gripping speed

The gripping speed can be presented as the average angular velocity or the average finger tip speed. The average angular velocity, ω are taken as the maximum angular deflexion, $\theta_1^{\max}$, of the MP joint divided by the time, t, taken to close the finger to this point:

$$\begin{aligned} \omega &= \theta_1^{\max}/t \qquad (A\text{-}13) \\ &= 75 / 4.85 \\ &= 15.48 \text{ degrees/sec} \end{aligned}$$

The average tip speed, v, is given the distance travelled by the tip of the finger, d, divided by the time of closure, t:

$$\begin{aligned} v &= d / t \qquad (A\text{-}14) \\ &= 158 / 4.85 \\ &= 32.58 \text{ mm/sec} \end{aligned}$$

The velocity has to be scaled up using Equation A-12.

The average angular speed of the thumb during opposition, Ω, is calculated using Equation A-13. Therefore:

$$\begin{aligned} \Omega &= 110 / 2.14 \\ &= 51.5 \text{ degrees/sec} \end{aligned}$$

A.7.3 Grip forces

The mechanism to determine the grip force has to be calibrated. A number of weights are put on the balloon and converted into forces using Equation A-1. The weight and the equivalent forces and corresponding water levels are given by Table A-3.

Water level (mm)	**Weight** (g)	**Force** (N)
3	53	0.52
6	106	1.04
9	159	1.56
12	212	2.08
15	265	2.60
18	318	3.12

Table A-5: The grasp force calibration data.

These points are used to determine the calibration function for the mechanism. The system is highly linear for the region in which is the tests on the hand was performed. The calibration function for the applied force, F, as a function of the rise in the water level, h, is given as:

$$F = 0.173 \cdot h \qquad (A\text{-}15)$$

The water level displacements are converted using Equation A-5 and is given in Table A-4.

	Water level (mm)	Force (N)
Grip force	6	1.04
Pinch force	15	2.60

Table A-6: The grasping forces of the hand

APPENDIX B

COMPUTER PROGRAMS AND DEVELOPED CODE

B.1 Determining the analytical solution

The optimisation program used to determine the finger trajectory is “Eureka.exe”. The interface for the program is shown in Figure B-1. The input for the program can be done manually (Edit) or can be read from an input file. Various tests had to be performed changing the different variables in the analytical model. The program can only handle a limited number of variable which forced the author to develop software which can use the variables as input and convert it into an input deck for the optimisation program. The executable software performing this function is “input.exe” and the code is presented in its Fortran format in “input.for”. The output of the Eureka software can be presented on the screen (Solution) or written to an output file. To make the results understandable it was written to an output file and software was developed to read this output file and convert the data into stick figures presenting the finger closing trajectory. The executable software developed for this purpose is “fingplot.exe” while the code is presented in its Fortran format in “fingplot.for”.

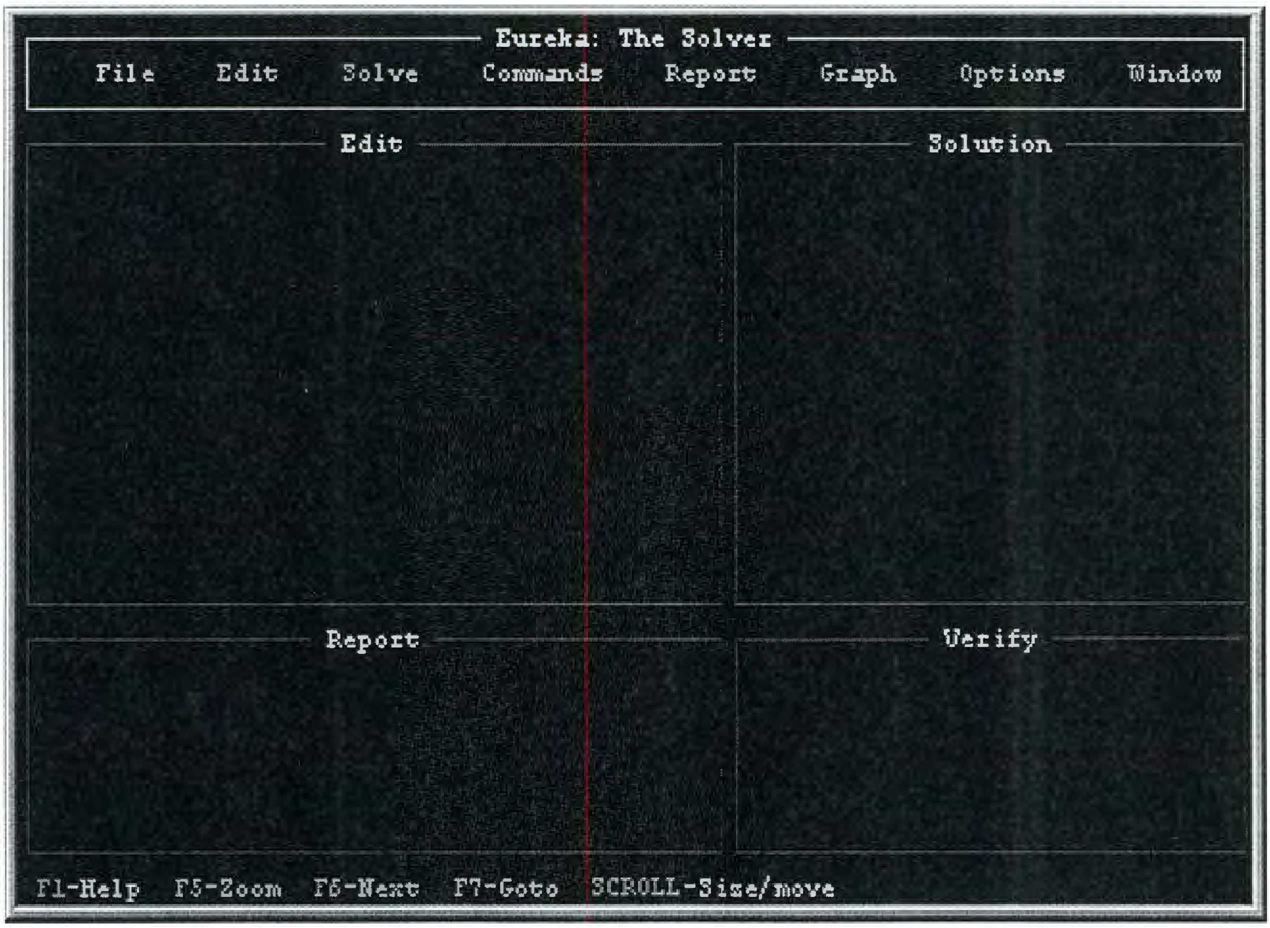

Figure B-1: The interface of the Eureka optimisation program.

B.1.1 Writing the input deck (input.for)

```
c--Declarations
      REAL B(5),l(3),r(5),K(3),pi,lock(3)
      CHARACTER*1 char(5)
      DATA char/'a','b','c','d','e'/

      pi=3.14159

c--Read the input variables
      WRITE(*,*) 'Enter the five guide angles (B)?'
      READ(*,*) B(1),B(2),B(3),B(4),B(5)
      WRITE(*,*) 'Enter the five guide radii (r)?'
      READ(*,*) r(1),r(2),r(3),r(4),r(5)
      WRITE(*,*) 'Enter the three input lengths (l)?'
      READ(*,*) l(1),l(2),l(3)
      WRITE(*,*) 'Enter the three spring constants (K)?'
      READ(*,*) K(1),K(2),K(3)
      WRITE(*,*) 'Enter the maximum deflexion angle for each joint?'
      READ(*,*) lock(1),lock(2),lock(3)

c--Open the output file
      OPEN(1,FILE='f:\eureka\finger.eka')

c--Write the output file

c--Write the value of all the variables
      DO i=1,5
      WRITE(1,100) char(i), B(i)
100   FORMAT('; B',A1,'=',F5.1)
      END DO
      WRITE(1,*)

      DO i=1,5
      WRITE(1,200) char(i), r(i)
200   FORMAT('; r',A1,'=',F5.3)
      END DO
      WRITE(1,*)

      DO i=1,3
      WRITE(1,300) char(i), l(i)
300   FORMAT('; l',A1,'=',F5.3)
      END DO
      WRITE(1,*)

      DO i=1,3
      WRITE(1,400) char(i), K(i)
400   FORMAT('; K',A1,'=',F5.3)
      END DO
      WRITE(1,*)

      DO i=1,3
      WRITE(1,500) char(i), lock(i)
500   FORMAT('; Stop ',A1,'=',F5.1)
      END DO
      WRITE(1,*)

c--Convert angles into radians
      DO i=1,5
       B(i)=pi*B(i)/180
      END DO

      DO i=1,3
       lock(i)=pi*lock(i)/180
```

```
      END DO


       WRITE(1,900)
900    FORMAT('F=')
      WRITE(1,*)

c--Write the moment equations
       WRITE(1,1000) r(1),B(1),r(2),B(2)
1000   FORMAT('Aa1=',F8.6,'*sin(',F8.6,'+Oa)-',F8.6,'*sin(',F8.6,')')
       WRITE(1,1010) r(1),B(1),r(2),B(2),l(1)
1010   FORMAT('Aa2=',F8.6,'*cos(',F8.6,'-Oa)-',F8.6,'*cos(',F8.6,')+'
   &       ,F8.6)
       WRITE(1,1020)
1020   FORMAT('LLa=(Aa1^2+Aa2^2)^0.5')
       WRITE(1,1030) r(2),B(2),l(1),r(2),B(2)
1030   FORMAT('Ma=F*(',F8.6,'*Aa2/LLa*sin(',F8.6,')+Aa1/LLa*('
   &       ,F8.6,'-',F8.6,'*cos(',F8.6,')))')
      WRITE(1,*)


       WRITE(1,2000) r(2),B(2),r(3),B(3)
2000   FORMAT('Ab1=',F8.6,'*sin(',F8.6,'+Ob)-',F8.6,'*sin(',F8.6,')')
       WRITE(1,2010) r(2),B(2),r(3),B(3),l(2)
2010   FORMAT('Ab2=',F8.6,'*cos(',F8.6,'-Ob)-',F8.6,'*cos(',F8.6,')+'
   &       ,F8.6)
       WRITE(1,2020)
2020   FORMAT('LLb=(Ab1^2+Ab2^2)^0.5')
       WRITE(1,2030) r(3),B(3),l(2),r(3),B(3)
2030   FORMAT('Mb=F*(',F8.6,'*Ab2/LLb*sin(',F8.6,')+Ab1/LLb*('
   &       ,F8.6,'-',F8.6,'*cos(',F8.6,')))')
      WRITE(1,*)

       WRITE(1,3000) r(4),B(4),r(5),B(5)
3000   FORMAT('Ac1=',F8.6,'*sin(',F8.6,'+Oc)-',F8.6,'*sin(',F8.6,')')
       WRITE(1,3010) r(4),B(4),r(5),B(5),l(3)
3010   FORMAT('Ac2=',F8.6,'*cos(',F8.6,'-Oc)-',F8.6,'*cos(',F8.6,')+'
   &       ,F8.6)
       WRITE(1,3020)
3020   FORMAT('LLc=(Ac1^2+Ac2^2)^0.5')
       WRITE(1,3030) r(5),B(5),l(3),r(5),B(5)
3030   FORMAT('Mc=F*(',F8.6,'*Ac2/LLc*sin(',F8.6,')+Ac1/LLc*('
   &       ,F8.6,'-',F8.6,'*cos(',F8.6,')))')
      WRITE(1,*)

       WRITE(1,4000) K(1)
4000   FORMAT (F5.3,'*Oa=Ma')
       WRITE(1,4010) K(2)
4010   FORMAT (F5.3,'*Ob=Mb')
       WRITE(1,4020) K(3)
4020   FORMAT (F5.3,'*Oc=Mc')
      WRITE(1,*)

c--Write the total deformation energy equation
       WRITE(1,5000) K(1),K(2),K(3)
5000   FORMAT('U=0.5*F*1000000*(',F8.6,'*Oa^2+',F8.6,
   &       '*Ob^2+',F8.6,'*Oc^2)')
      WRITE(1,*)

c--Set the energy as the minimisation variable
       WRITE(1,6000)
6000   FORMAT('$ min(U)')
      WRITE(1,*)
```

```
c--Set the boundary conditions
      WRITE(1,7000) lock(1)
7000  FORMAT('0 <= Oa < ',F8.6)
      WRITE(1,7010) lock(2)
7010  FORMAT('0 <= Ob < ',F8.6)
      WRITE(1,7020) lock(3)
7020  FORMAT('0 <= Oc < ',F8.6)
      WRITE(1,*)

c--Set an estemate for the deflexion angles
      WRITE(1,8000)
8000  FORMAT('Oa  := 1.0')
      WRITE(1,8010)
8010  FORMAT('Ob  := 1.0')
      WRITE(1,8020)
8020  FORMAT('Oc  := 1.0')

      CLOSE(1)
      WRITE(*,*) 'OUTPUT WRITTEN TO:  "finger.eka" '
      END
```

B.1.2 Plotting the stick figures (fingplot.for)

```
c--Include graphic routines
*$noextensions
*$include gksdefn
c--Declare subroutines
      INTEGER tnum,set,i,j
      REAL x(10,4), y(10,4), phi(10,3),len(3),indx(6)
      REAL breedth,height
      CHARACTER*3 ind
      CHARACTER*12 filename
      CHARACTER*22 path1
      CHARACTER*1 path2(22)
      CHARACTER*22 path3
      EQUIVALENCE (path1,path2(1))
      EQUIVALENCE (filename,path2(11))
      EQUIVALENCE (path3,path2(1))

c--Set path for input file
      path1='f:\eureka\'

c--Set constants
      tnum=1
      repeat=5

c--Read the name of the input file
      WRITE(*,*) 'Enter name of Input file (f:\eureka\):'
      READ(*,10) filename
10    FORMAT(A12)

c--Read input file
      OPEN (1,FILE=path3)

c--The indicatorcounting the number input decks in the file
        set=0
      LOOP
        set=set+1

c--Detect the starting line for each input deck
      LOOP
        READ(1,1000,END=2000) ind
1000    FORMAT(A3)
      UNTIL (ind.EQ.' Mc')
```

```
c--Read the deflexion angles
      DO i=1,6
        READ(1,1100,END=2100) indx(i)
1100     FORMAT(13X,E13.1)
      END DO
        phi(set,1)=indx(2)
        phi(set,2)=indx(4)
        phi(set,3)=indx(6)
      UNTIL (set.EQ.10)
      GOTO 2100

2000   CONTINUE
      set=set-1
2100   CONTINUE

      UNTIL (set.EQ.10)
      CLOSE (UNIT=1)

c--Input the finger lengths
       WRITE(*,*)
       WRITE(*,100)
100    FORMAT (1h ,'Input finger lengths (l1,l2,l3):')
       READ (*,*) len(1),len(2),len(3)

c--Set the origin
      DO j=1,set
      x(j,1)=0
      y(j,1)=0
      END DO

c--Determine the co-ordinates for all the joints
      DO j=1,set

      x(j,2)=len(1)*sin(phi(j,1))
      y(j,2)=len(1)*cos(phi(j,1))

      x(j,3)=x(j,2)+len(2)*sin(phi(j,1)+phi(j,2))
      y(j,3)=y(j,2)+len(2)*cos(phi(j,1)+phi(j,2))

      x(j,4)=x(j,3)+len(3)*sin(phi(j,1)+phi(j,2)+phi(j,3))
      y(j,4)=y(j,3)+len(3)*cos(phi(j,1)+phi(j,2)+phi(j,3))
      END DO

c--Determine the window size
      height=len(1)+len(2)+len(3)
      breedth=2*height

c--Set the graphics indicators
       CALL GOPKS(0)
       CALL GOPWK(14,0,2)
       CALL GACWK(14)

c--Set the window size
       CALL GSWN(tnum,0,breedth,-height,height)
       CALL GSVP(tnum,0.1,0.9,0.1,0.9)
       CALL GSELNT(tnum)

c--Draw the stick finger trajectory
c--Repeat the animation
      DO jj=1,repeat
c--Animate the finger trajectory
      DO j=1,set
c--Draw one stick stick finger
      DO i=1,3
```

```
       CALL LINE( x(j,i), y(j,i), x(j,i+1), y(j,i+1), set )
      END DO
       CALL PAUSE(4.0)
       IF (jj.EQ.repeat) GOTO 1111
       CALL GCLRWK(14,1)
1111   CONTINUE
      END DO
      END DO

c--Set closing graphics parameters
       CALL GDAWK(14)
       CALL GCLWK(14)
       CALL GCLKS

       END

c--subroutine to pause the animation
       SUBROUTINE PAUSE( SECONDS )
       REAL SECONDS
       INTEGER LPS, TICS
PARAMETER (LPS=50000)
       SECONDS = SECONDS * LPS
       DO TICS=1, INT( SECONDS )
       ENDDO

       END
```

B.2 Lego software

The definition of the Lego subroutines used in the software to control the hand is presented in the "Lego.doc" file. The declarations for these files in the format to be used in Visual Basic is presented in "Lego.bas".

B.2.1 Lego.doc

Runtime package for LEGO Interface B

A DOS & Windows package for interfacing LEGO Interface B through ordinary programming languages
User's Manual

Written by:
Pyramide Data i/s.

How to use the runtime library

The runtime library for interfacing Interface B can be used under DOS & Windows. For DOS use, it is currently only possible using the C or the C++ programming languages. Windows users can however use any programming language capable of using DLL files.

Using the runtime library for DOS

The necessary type and prototype declarations are found in the file **lego4dos.h**. To link the package with your program you have to include the file **lego4dos.obj** in your project file.

Using the runtime library for Windows

When programming under Windows the LEGO interface is reached via a DLL. Check your programming manual to see how to interface a DLL with your programming language. C programmers can use the file **lego.h** to get type and prototype declarations, and then include the file **lego.lib** into the project file. **lego.lib** is not a true library file, it only contains information about how to interface the DLL.

Borland PASCAL users can use the TPU-file **lego.tpw**. The TPU-file serves the same purpose for the PASCAL program as the files **lego.lib** and **lego.h** for the C program: To create a type safe interface to the DLL file.

Visual Basic users can use the file **logo.bas** for a type safe interface to the DLL. Include it in the **general** objet in a form in the **declaration** procedure.

If you use an other programming language than the three mentioned above, you have to create your own interface-file to communicate with the DLL. When you are declaring the miscellaneous procedures and functions in your programming language we recommend that you refer to the procedures and functions via their index number.

Functions for communicating with Interface B.

I the following we describe every function you have access to through the **lego.dll**. The first line contains the index number the function has in the DLL. Next follows the function head shown in C-style and in PASCAL-style.

Index 31
ErrorCode IFB_InitLegoInterface (char *Inittext, char *Answertext, int Port)
FUNCTION IFB_InitLegoInterface(inittext, answertext: PChar; port: INTEGER) : ErrorCode

Prepare computer to communicate with interface B and initialize the interface if present.
Inittext: Must contain the following text: ***Do you byte , when I knock?***
Answertext: ***Just a bit off the block!***
Port: The port argument must be 1, 2, 3 or 4.
Returning ErrorCode: Is one of the following:
OK, WrongText, WrongPort, NoInterfaceBoxPresent.
If **OK**, the interface is connected.
If **WrongText**: You are using the wrong text. The answertext is wrong.
If **WrongPort**: You have tried to use an unsupported port.
If **NoInterfaceBoxPresent**: There is no interface box on the specified port.

Index 30
int IFB_Raw(int InputPort)
FUNCTION IFB_Raw(InputPort: INTEGER) : INTEGER

Returns the raw value associated to the input port.
InputPort: Must be in the range 1..8.
Returning -1 if InputPort is illegal.

Index 28
bool IFB_Boolean(int InputPort)
FUNCTION IFB_Boolean(InputPort: INTEGER) : BOOLEAN

Returns the digital status associated to the input port.
InputPort: Must be in the range 1..8.
Returning false if InputPort is illegal.

Index 17
void IFB_OnLeft(char *OutputPortList)
PROCEDURE IFB_OnLeft(OutputPortList: PChar)

Turn on and set direction left for the output ports contained in OutputPortList.
OutPutPortList: May contain up to eight different port names.

Index 16
void IFB_OnRight(char *OutputPortList)
PROCEDURE IFB_OnRight(OutputPortList: PChar)

Turn on and set direction right for the output ports contained in OutputPortList.
OutPutPortList: May contain up to eight different port names.

Index 15
void IFB_On(char *OutputPortList)
PROCEDURE IFB_On(OutputPortList: PChar)

Turn on the output ports contained in OutputPortList.
OutPutPortList: May contain up to eight different port names.

Index 13
void IFB_Off(char *OutputPortList)
PROCEDURE IFB_Off(OutputPortList: PChar)

Turn off the output ports contained in OutputPortList.
OutPutPortList: May contain up to eight different port names.

Index 11
void IFB_SetLeft(char *OutputPortList)
PROCEDURE IFB_SetLeft(OutputPortList: PChar)
Set direction left for output ports contained in OutputPortList.
OutPutPortList: May contain up to eight different port names.

Index 10
void IFB_SetRight(char *OutputPortList)
PROCEDURE IFB_SetRight(OutputPortList: PChar)
Set direction right for the output ports contained in OutputPortList.
OutPutPortList: May contain up to eight different port names.

Index 7
void IFB_SetPower(char *OutputPortList, int Level)
PROCEDURE IFB_SetPower(OutputPortList: PChar; Level: INTEGER)
Set power level for the output ports contained in OutputPortList.
OutPutPortList: May contain up to eight different port names.
Level: Must be a value in the range 0..7.

Index 6
void IFB_OnFor(char *OutputPortList, int Time)
PROCEDURE IFB_OnFor(OutputPortList: PChar; Time: INTEGER)
Turn the output ports contained in OutputPortList on for a limited time.
OutPutPortList: May contain up to eight different port names.
Time: In 10th of seconds and must be in the range 0..255. Illegal values for Time results in ignoring the command.

B.2.2 Lego.bas

```
Const OK = 0
Const WrongText = 1
Const WrongPort = 2
Const NoInterfaceBoxPresent = 3

Declare Function IFB_InitLegoInterface Lib "lego.dll" Alias "#31" (ByVal inittext As String, ByVal Answertext As String,
ByVal portnr As Integer) As Integer
Declare Function IFB_Raw Lib "lego.dll" Alias "#30" (ByVal InputPort As Integer) As Integer
Declare Function IFB_Boolean Lib "lego.dll" Alias "#28" (ByVal InputPort As Integer) As Integer
Declare Sub IFB_OnLeft Lib "lego.dll" Alias "#17" (ByVal OutputPortList As String)
Declare Sub IFB_OnRight Lib "lego.dll" Alias "#16" (ByVal OutputPortList As String)
Declare Sub IFB_On Lib "lego.dll" Alias "#15" (ByVal OutputPortList As String)
Declare Sub IFB_Off Lib "lego.dll" Alias "#13" (ByVal OutputPortList As String)
Declare Sub IFB_SetLeft Lib "lego.dll" Alias "#11" (ByVal OutputPortList As String)
Declare Sub IFB_SetRight Lib "lego.dll" Alias "#10" (ByVal OutputPortList As String)
Declare Sub IFB_SetPower Lib "lego.dll" Alias "#7" (ByVal OutputProtList As String, ByVal Levels As Integer)
Declare Sub IFB_OnFor Lib "lego.dll" Alias "#6" (ByVal OutputPortList As String, ByVal OnforTime As Integer)
```

B.3 Developed software to control the hand (Visual Basic)

B.3.1 Global declarations and subroutines (hand.bas)

Declarations:

```
' Error messages for interface box
Global Const OK = 0
Global Const WrongText = 1
Global Const WrongPort = 2
Global Const NoInterfaceBoxPresent = 3

'Set communication mode for the I/O card
Global Const In_Mode = 146
```

```
Global Const Out_Mode = 128

'Set the time constant for holding button down
Global Const hold_time = 5

'Dimension the the input bits for position indicators
Global ext_bit1, ext_bit2, ext_bit3, ext_bit4, ext_bit5
Global thumb_bit0, thumb_bit90, thumb_bit110

'Dimension the variables indicating motors switched off
Global thumb_Off, index_Off, finger_Off, oppose_Off, abduct_Off

' Set path for the help file
Global Const help_dir = ""

' Set name of the help file
Global Const help_file = "hand.txt"

' Set pages names for help file
Global Const general = 1
Global Const automatic = 2
Global Const manual = 3
Global Const auto_run = 4
Global Const manual_run = 5
Global Const sensors = 6

' Dimension indicators
Global click_ind     'indicates which button was used
Global help_ind, current_page, help_start     'indicates which help page to show
Global time_count   'counter for each time interval of timer
Global PARK          'set when the hand is already parked
Global manual_busy

'Manual window button indicators
Global thumb_open, index_open, finger_open, rotate_out, stop_button

' Set motor stop currents
Global Const thumb_stop = 200, thumb_step = 20, thumb_max = 300
Global Const finger_stop = 320, finger_step = 20, finger_max = 420
Global Const index_stop = 100, index_step = 10, index_max = 140

' Declare Lego Interface subroutines
Declare Function IFB_InitLegoInterface Lib "lego.dll" Alias "#31" (ByVal inittext As String, ByVal Answertext As String, ByVal portnr As Integer) As Integer
Declare Function IFB_Raw Lib "lego.dll" Alias "#30" (ByVal InputPort As Integer) As Integer
Declare Function IFB_Boolean Lib "lego.dll" Alias "#28" (ByVal InputPort As Integer) As Integer
Declare Sub IFB_OnLeft Lib "lego.dll" Alias "#17" (ByVal OutputPortList As String)
Declare Sub IFB_OnRight Lib "lego.dll" Alias "#16" (ByVal OutputPortList As String)
Declare Sub IFB_On Lib "lego.dll" Alias "#15" (ByVal OutputPortList As String)
Declare Sub IFB_Off Lib "lego.dll" Alias "#13" (ByVal OutputPortList As String)
Declare Sub IFB_SetLeft Lib "lego.dll" Alias "#11" (ByVal OutputPortList As String)
Declare Sub IFB_SetRight Lib "lego.dll" Alias "#10" (ByVal OutputPortList As String)
Declare Sub IFB_Setpower Lib "lego.dll" Alias "#7" (ByVal OutputProtList As String, ByVal Levels As Integer)
Declare Sub IFB_Onfor Lib "lego.dll" Alias "#6" (ByVal OutputPortList As String, ByVal OnforTime As Integer)
```

Subroutines:

```
Function bin (num)
ext_bit1 = True
ext_bit2 = True
ext_bit3 = True
ext_bit4 = True
```

```
ext_bit5 = True
thumb_bit0 = True
thumb_bit90 = True
thumb_bit110 = True

  Select Case (num)
  Case (128)
   thumb_bit110 = False
   GoTo 10
  Case (64)
   thumb_bit90 = False
   GoTo 10
  Case (32)
   thumb_bit0 = False
   GoTo 10
  Case (16)
   ext_bit5 = False
   GoTo 10
  Case (8)
   ext_bit4 = False
   GoTo 10
  Case (4)
   ext_bit3 = False
   GoTo 10
  Case (2)
   ext_bit2 = False
   GoTo 10
  Case (1)
   ext_bit1 = False
   GoTo 10
  End Select

   diff = num

  If diff >= 128 Then
   diff = diff - 128
   thumb_bit110 = False
  End If
  If diff >= 64 Then
   diff = diff - 64
   thumb_bit90 = False
  End If
  If diff >= 32 Then
   diff = diff - 32
   thumb_bit0 = False
  End If
  If diff >= 16 Then
   diff = diff - 16
   ext_bit5 = False
  End If
  If diff >= 8 Then
   diff = diff - 8
   ext_bit4 = False
  End If
  If diff >= 4 Then
   diff = diff - 4
   ext_bit3 = False
  End If
  If diff >= 2 Then
   diff = diff - 2
   ext_bit2 = False
  End If
  If diff = 1 Then
   diff = diff - 2
```

```
     ext_bit1 = False
    End If
10
 End Function

Sub bit_reset ()
    ext_bit1 = False
    ext_bit2 = False
    ext_bit3 = False
    ext_bit4 = False
    ext_bit5 = False
    thumb_bit0 = False
    thumb_bit90 = False
    thumb_bit110 = False
End Sub

Sub info_box (head, line1, line2, line3, line4, line5, line6)
    form2.Cls
    form2.Visible = True
    blank = "              "
    form2.FontSize = 13.5
    form2.Print blank + head
    form2.Print
    form2.FontSize = 8.5
    form2.Print blank + line1
    form2.Print blank + line2
    form2.Print blank + line3
    form2.Print blank + line4
    form2.Print blank + line5
    form2.Print blank + line6
End Sub

Sub reset_Off ()
    thumb_Off = False
    index_Off = False
    finger_Off = False
    oppose_Off = False
    abduct_Off = False
End Sub

Sub wait (sec)
' PAUSE THE EXECUTION FOR 'sec'

   'Reset timer counter used in the Timer Event
    time_count = 0

   'Activate timer until puase time is reached time
    form1.Timer1.Enabled = True
      Do
      DoEvents
      Loop Until time_count = sec

   'Deactivate timer
    form1.Timer1.Enabled = False
End Sub

Sub write_help (help_page)
Dim help_text As String * 100
Dim help_flag As String * 1

   ' Cet tab space
    blank_space = "   "
   ' Clear the help screen and switch it on
   If form6.Visible = False Then
```

```
     help_start = True
   Else
     help_start = False
   End If
   form6.Cls
   form6.Visible = True

   ' Set path to lacate help file
    help_path = help_dir & help_file

   'OPEN help file
    Open help_path For Input As #1

     ' Search for the right help page
      ' help_page = help_ind
      Do
        Input #1, help_flag
      Loop Until help_flag = help_page

     ' Write the header in different larger font
      Input #1, header
      form6.FontSize = 16
      form6.Print
      header = "              " & header
      form6.Print header
      form6.Print

     ' Write the text of the help file
      form6.FontSize = 8.25
     Do
        Input #1, help_text
        help_flag = Mid(help_text, 10)
        help_line = blank_space & help_text
        form6.Print help_line
     Loop Until help_flag = "-"
     'CLOSE help file
     Close 1
End Sub

Sub MODE_SELECTION ()
    'Reset
      click_ind = ""
      form2.Visible = False

    'Write message
    Call info_box("SELECT A MODE", "FLEX = POWER MODE", "flex = PRECISION MODE", "", "", "", "")

    'Wait for selection signal
    Do
       DoEvents
       'Select Power_Mode
       If click_ind = "FLEX" Then Call Power_Mode
       'Select Precision_Mode
       If click_ind = "flex" Then Call Precision_Mode
    Loop Until aa = 999
End Sub

Sub Power_Mode ()
    'Reset
     click_ind = ""
     form2.Visible = False

    'Write instructions
```

```
   Call info_box("SELECT HAND SHAPE", "FLEX    = Small", "flex    = Large", "BOTH    = Sphere", "both    = side",
"EXTEND = Reset to PARK", "extend = Reselect Mode")

  'Wait for signal
   Do
   DoEvents
     'Select hand shape
     If click_ind = "flex" Then Call Large_Grip
     If click_ind = "FLEX" Then Call Small_Grip
     If click_ind = "both" Then Call Side_Grip
     If click_ind = "BOTH" Then Call Sphere_Grip
     If click_ind = "extend" Then Call MODE_SELECTION  'Reselect Mode
     If click_ind = "EXTEND" Then
      PARK = True
      Call Park_grip  'Reset to Park Mode
     End If
   Loop Until aa = 99
End Sub

Sub Precision_Mode ()
  'Reset
  click_ind = ""
  form2.Visible = False

  'Write instructions
  Call info_box("SELECT HAND SHAPE", "FLEX = OK", "flex = Needle", "BOTH = Chuck", "both = Tip", "EXTEND =
Reset to PARK", "extend = Reselect Mode")

  'Wait for selection signal
  Do
   DoEvents
     'Select hand shape
     If click_ind = "flex" Then Call Needle_Grip
     If click_ind = "FLEX" Then Call OK_Grip
     If click_ind = "both" Then Call Tip_Grip
     If click_ind = "BOTH" Then Call Chuck_Grip
     If click_ind = "extend" Then Call MODE_SELECTION  'Reselect Mode
     If click_ind = "EXTEND" Then
      PARK = True
      Call Park_grip  'Reset to Park Mode
     End If
  Loop Until aa = 99
End Sub

Sub Chuck_Grip ()
  'Switch Info window off
  form2.Visible = False

  'Direction and power
  IFB_SetRight "b"
  IFB_SetLeft "acd"
  IFB_Setpower "d", 5

   'Rotate Thumb
  IFB_Onfor "d", 20
 Do
   DoEvents
    port_bite = form1.IOPORT2.PortData
    bin_code = bin(port_bite)
 Loop Until thumb_bit90 = True
  Call wait(1)
  IFB_Off "d"

   'Flex 3-fingers then index
```

```
  IFB_Onfor "c", 15
  IFB_Onfor "b", 10

  'Open thumb slightly
  IFB_Onfor "a", 2

CHUCK_WAIT:  'HAND STILL OPEN, WAITING FOR SIGNAL

 'Switch Info window off
  form2.Visible = False
 'Reset click indicator
  click_ind = ""
 'Write information box
  Call info_box("SELECT CONTROL SIGNAL", "FLEX = Close to max force", "flex = Close to next force step",
"EXTEND = Reset to park mode", "", "", "")


  'Wait for signal
  Do
   DoEvents
   If click_ind = "flex" Then GoTo CHUCK_STEPS  'close in steps
   If click_ind = "FLEX" Then GoTo CHUCK_MAX   'close to the max
   If click_ind = "EXTEND" Then Call Park_grip  'go back to park
  Loop Until a = 99


CHUCK_STEPS:     'GRIP IN PRESET FORCE STEPS

  'Switch information box off
  form2.Visible = False

  'Set switch-off current for thumb
  thumb_value = thumb_stop
  index_value = index_stop

  For i = 1 To 3      'BEGIN FORCE STEP
     click_ind = ""
     Call reset_Off

 'Close the thumb and index finger
  IFB_SetRight "ab"
  IFB_Onfor "b", 2
  IFB_Onfor "a", 10
  Call wait(1)

 'Do until force limit is reached in thumb or index finger
 'and switch motors off
   Do
   DoEvents
     thumb_current = IFB_Raw(1)
    If thumb_current > thumb_value Then
      thumb_Off = True
      IFB_Off "a"
    End If
     index_current = IFB_Raw(2)
    If index_current > index_value Then
      index_Off = True
      IFB_Off "b"
    End If
   Loop Until (index_Off And thumb_Off) = True
     IFB_Off "ab"

    'Reset switch-off current for each motor
     thumb_value = thumb_value + thumb_step
```

```
    index_value = index_value + index_step

  'Write information box
  Call info_box("SELECT CONTROL SIGNAL", "FLEX = Close to max force", "flex = Close to next force step",
"EXTEND = Reset to park mode", "extend = Opens the hand", "", "")

  'Wait for signal
  Do
   DoEvents
   If click_ind = "extend" Then GoTo CHUCK_RELEASE 'Release object
   If click_ind = "EXTEND" Then Call Park_grip     'Release and park
   If click_ind = "FLEX" Then GoTo CHUCK_MAX       'Grip to the maximum
  Loop Until click_ind = "flex"                    'Go to next step

 Next i      'NEXT FORCE STEP

CHUCK_MAX:     'GRIP TO THE MAXIMUM FORCE

  'Switch Info window off
  form2.Visible = False

 'Reset indicators
  click_ind = ""
  Call reset_Off

  'Close the thumb and index finger
  IFB_SetRight "ab"
  IFB_Onfor "b", 2
  IFB_Onfor "a", 10
  Call wait(5)

 'Do until max force limit is reached in thumb or index finger
 'and switch motors off
   Do
   DoEvents
    thumb_current = IFB_Raw(1)
    index_current = IFB_Raw(2)
   Loop Until (thumb_current > thumb_max) Or (index_current > index_max)
    IFB_Off "ab"

  'Write Info box
  Call info_box("SELECT CONTROL SIGNAL", "EXTEND = Reset to park mode", "extend = Opens the hand", "", "", "",
"")

  'Wait for signal
   Do
    DoEvents
    If click_ind = "extend" Then GoTo CHUCK_RELEASE 'Release object
    If click_ind = "EXTEND" Then Call Park_grip     'Release and park
   Loop Until click_ind = "EXTEND"


CHUCK_RELEASE:     'RELEASE THE GRIP ON THE OBJECT FOR REGRIPPING
 'Reset
  click_ind = ""

 'Release grip
  IFB_SetLeft "ab"

  'Extend thumb and index finger
  IFB_Onfor "ab", 5

GoTo CHUCK_WAIT
End Sub
```

```
Sub Large_Grip ()
  'Switch Info window off
  form2.Visible = False

  'Direction and power
  IFB_SetRight "b"
  IFB_SetLeft "acd"
  IFB_Setpower "d", 5

   'Rotate Thumb
  IFB_Onfor "d", 20
 Do
   DoEvents
    port_bite = form1.IOPORT2.PortData
    bin_code = bin(port_bite)
 Loop Until thumb_bit90 = True
  Call wait(1)
  IFB_Off "d"

   'Flex 3-fingers then index slightly
  IFB_Onfor "bc", 7

  'Extend thumb
  IFB_Onfor "a", 10


LARGE_WAIT:   'HAND STILL OPEN, WAITING FOR SIGNAL

 'Switch Info window off
  form2.Visible = False
 'Reset click indicator
  click_ind = ""
 'Write information box
  Call info_box("SELECT CONTROL SIGNAL", "FLEX = Close to max force", "flex = Close to next force step",
"EXTEND = Reset to park mode", "", "", "")


  'Wait for signal
  Do
   DoEvents
   If click_ind = "flex" Then GoTo LARGE_STEPS  'close in steps
   If click_ind = "FLEX" Then GoTo LARGE_MAX    'close to the max
   If click_ind = "EXTEND" Then Call Park_grip  'go back to park
  Loop Until a = 99


LARGE_STEPS:      'GRIP IN PRESET FORCE STEPS

  'Switch information box off
  form2.Visible = False

  'Set switch-off current for each motor
  thumb_value = thumb_stop
  index_value = index_stop
  finger_value = finger_stop

  For i = 1 To 3     'BEGIN FORCE STEP
    click_ind = ""
    Call reset_Off

  'Close thumb and all fingers
    IFB_SetLeft "c"
    IFB_SetRight "ab"
```

```
       IFB_Onfor "abc", 30
       Call wait(5)

   'Do until force limits are reached and switch motors off
     Do
      DoEvents
       thumb_current = IFB_Raw(1)
       If thumb_current > thumb_value Then
        thumb_Off = True
        IFB_Off "a"
       End If
       index_current = IFB_Raw(2)
       If index_current > index_value Then
        IFB_Off "b"
        index_Off = True
       End If
       finger_current = IFB_Raw(3)
       If finger_current > finger_value Then
        IFB_Off "c"
        finger_Off = True
       End If
     Loop Until (thumb_Off And index_Off And finger_Off) = True
      'Reset switch-off current for each motor
       thumb_value = thumb_value + thumb_step
       index_value = index_value + index_step
       finger_value = finger_value + finger_step

    'Write information box
    Call info_box("SELECT CONTROL SIGNAL", "FLEX = Close to max force", "flex = Close to next force step",
"EXTEND = Reset to park mode", "extend = Opens the hand", "", "")

    'Wait for signal
    Do
     DoEvents
     If click_ind = "extend" Then GoTo LARGE_RELEASE 'Release object
     If click_ind = "EXTEND" Then Call Park_grip     'Release and park
     If click_ind = "FLEX" Then GoTo LARGE_MAX       'Grip to the maximum
    Loop Until click_ind = "flex"                    'Go to next step

   Next i         'NEXT FORCE STEP


LARGE_MAX:    'GRIP TO THE MAXIMUM FORCE

    'Switch Info window off
    form2.Visible = False

   'Reset indicators
    click_ind = ""
    Call reset_Off

   'Close all the fingers
    IFB_SetLeft "c"
    IFB_SetRight "ab"
    IFB_Onfor "abc", 30
    Call wait(5)

   'Do until force limits are reached and switch motors off
    Do
     DoEvents
       thumb_current = IFB_Raw(1)
       If thumb_current > thumb_max Then
        thumb_Off = True
        IFB_Off "a"
```

```
      End If
      index_current = IFB_Raw(2)
      If index_current > index_max Then
       IFB_Off "b"
       index_Off = True
      End If
      finger_current = IFB_Raw(3)
      If finger_current > finger_max Then
       IFB_Off "c"
       finger_Off = True
      End If
    Loop Until (thumb_Off And index_Off And finger_Off) = True

    'Write Info box
    Call info_box("SELECT CONTROL SIGNAL", "EXTEND = Reset to park mode", "extend = Opens the hand", "", "", "",
"")

    'Wait for signal
     Do
      DoEvents
      If click_ind = "extend" Then GoTo LARGE_RELEASE 'Release object
      If click_ind = "EXTEND" Then Call Park_grip    'Release and park
     Loop Until click_ind = "EXTEND"


LARGE_RELEASE:
   'Reset
    click_ind = ""

   'Release grip
    IFB_SetLeft "ab"
    IFB_SetRight "c"

   'Extend all the fingers
    IFB_Onfor "abc", 7

GoTo LARGE_WAIT
End Sub

Sub Needle_Grip ()
    'Switch info window off
    form2.Visible = False

    'Direction and power
    IFB_SetRight "b"
    IFB_SetLeft "acd"
    IFB_Setpower "d", 5

     'Rotate Thumb
    IFB_Onfor "d", 20
   Do
     DoEvents
      port_bite = form1.IOPORT2.PortData
      bin_code = bin(port_bite)
   Loop Until thumb_bit90 = True
    Call wait(1)
    IFB_Off "d"

     'Flex 3-fingers then index
    IFB_Onfor "c", 30
    Call wait(10)
    IFB_Onfor "b", 10

    'Open thumb slightly
```

```
   IFB_Onfor "a", 2

NEEDLE_WAIT:  'HAND STILL OPEN, WAITING FOR SIGNAL

  'Switch Info window off
   form2.Visible = False
  'Reset click indicator
   click_ind = ""
  'Write information box
   Call info_box("SELECT CONTROL SIGNAL", "FLEX = Close to max force", "flex = Close to next force step",
"EXTEND = Reset to park mode", "", "", "")

   'Wait for signal
   Do
    DoEvents
    If click_ind = "flex" Then GoTo NEEDLE_STEPS  'close in steps
    If click_ind = "FLEX" Then GoTo NEEDLE_MAX    'close to the max
    If click_ind = "EXTEND" Then Call Park_grip  'go back to park
   Loop Until a = 99


NEEDLE_STEPS:       'GRIP IN PRESET FORCE STEPS

   'Switch information box off
   form2.Visible = False

   'Set switch-off current for thumb
   thumb_value = thumb_stop
   index_value = index_stop

   For i = 1 To 3       'BEGIN FORCE STEP
      click_ind = ""
      Call reset_Off

   'Close the thumb and index finger
   IFB_SetRight "ab"
   IFB_Onfor "b", 2
   IFB_Onfor "a", 10
   Call wait(1)

  'Do until force limit is reached in thumb or index finger
  'and switch motors off
    Do
    DoEvents
      thumb_current = IFB_Raw(1)
     If thumb_current > thumb_value Then
       thumb_Off = True
       IFB_Off "a"
     End If
      index_current = IFB_Raw(2)
     If index_current > index_value Then
       index_Off = True
       IFB_Off "b"
     End If
    Loop Until (index_Off And thumb_Off) = True
      IFB_Off "ab"

     'Reset switch-off current for each motor
      thumb_value = thumb_value + thumb_step
      index_value = index_value + index_step

   'Write information box
   Call info_box("SELECT CONTROL SIGNAL", "FLEX = Close to max force", "flex = Close to next force step",
"EXTEND = Reset to park mode", "extend = Opens the hand", "", "")
```

```
   'Wait for signal
   Do
    DoEvents
    If click_ind = "extend" Then GoTo NEEDLE_RELEASE 'Release object
    If click_ind = "EXTEND" Then Call Park_grip      'Release and park
    If click_ind = "FLEX" Then GoTo NEEDLE_MAX       'Grip to the maximum
   Loop Until click_ind = "flex"                     'Go to next step

  Next i       'NEXT FORCE STEP

NEEDLE_MAX:     'GRIP TO THE MAXIMUM FORCE

   'Switch Info window off
   form2.Visible = False

  'Reset indicators
   click_ind = ""
   Call reset_Off

   'Close the thumb and index finger
   IFB_SetRight "ab"
   IFB_Onfor "b", 2
   IFB_Onfor "a", 10
   Call wait(5)

  'Do until max force limit is reached in thumb or index finger
  'and switch motors off
    Do
    DoEvents
      thumb_current = IFB_Raw(1)
      index_current = IFB_Raw(2)
    Loop Until (thumb_current > thumb_max) Or (index_current > index_max)
      IFB_Off "ab"

   'Write Info box
   Call info_box("SELECT CONTROL SIGNAL", "EXTEND = Reset to park mode", "extend = Opens the hand", "", "", "",
"")

   'Wait for signal
    Do
     DoEvents
     If click_ind = "extend" Then GoTo NEEDLE_RELEASE 'Release object
     If click_ind = "EXTEND" Then Call Park_grip      'Release and park
    Loop Until click_ind = "EXTEND"


NEEDLE_RELEASE:     'RELEASE THE GRIP ON THE OBJECT FOR REGRIPPING
  'Reset
   click_ind = ""

  'Release grip
   IFB_SetLeft "ab"

   'Extend thumb and index finger
   IFB_Onfor "ab", 10

GoTo NEEDLE_WAIT
End Sub

Sub OK_Grip ()
   'Switch Info window off
   form2.Visible = False
```

```
  'Direction and power
  IFB_SetRight "b"
  IFB_SetLeft "ad"
  IFB_Setpower "d", 5

   'Rotate Thumb
  IFB_Onfor "d", 20

   'Detect 90 degree stop for thumb
 Do
   DoEvents
   port_bite = form1.IOPORT2.PortData
   bin_code = bin(port_bite)
 Loop Until thumb_bit90 = True
  Call wait(1)
  IFB_Off "d"

   'Flex index
  IFB_Onfor "b", 10

  'Open thumb slightly
  IFB_Onfor "a", 2

OK_WAIT:  'HAND STILL OPEN, WAITING FOR SIGNAL

  'Switch Info window off
   form2.Visible = False
  'Reset click indicator
   click_ind = ""
  'Write information box
   Call info_box("SELECT CONTROL SIGNAL", "FLEX = Close to max force", "flex = Close to next force step", "EXTEND = Reset to park mode", "", "", "")

   'Wait for signal
   Do
    DoEvents
    If click_ind = "flex" Then GoTo OK_STEPS  'close in steps
    If click_ind = "FLEX" Then GoTo OK_MAX   'close to the max
    If click_ind = "EXTEND" Then Call Park_grip  'go back to park
   Loop Until a = '99


OK_STEPS:     'GRIP IN PRESET FORCE STEPS

   'Switch information box off
   form2.Visible = False

   'Set switch-off current for thumb
   thumb_value = thumb_stop
   index_value = index_stop

   For i = 1 To 3      'BEGIN FORCE STEP
     click_ind = ""
     Call reset_Off

   'Close the thumb and index finger
   IFB_SetRight "ab"
   IFB_Onfor "b", 2
   IFB_Onfor "a", 10
   Call wait(1)

  'Do until force limit is reached in thumb or index finger
  'and switch motors off
    Do
```

```
    DoEvents
     thumb_current = IFB_Raw(1)
    If thumb_current > thumb_value Then
      thumb_Off = True
      IFB_Off "a"
    End If
     index_current = IFB_Raw(2)
    If index_current > index_value Then
      index_Off = True
      IFB_Off "b"
    End If
   Loop Until (index_Off And thumb_Off) = True
     IFB_Off "ab"

    'Reset switch-off current for each motor
     thumb_value = thumb_value + thumb_step
     index_value = index_value + index_step

   'Write information box
   Call info_box("SELECT CONTROL SIGNAL", "FLEX = Close to max force", "flex = Close to next force step",
"EXTEND = Reset to park mode", "extend = Opens the hand", "", "")

   'Wait for signal
   Do
    DoEvents
    If click_ind = "extend" Then GoTo OK_RELEASE   'Release object
    If click_ind = "EXTEND" Then Call Park_grip    'Release and park
    If click_ind = "FLEX" Then GoTo OK_MAX         'Grip to the maximum
   Loop Until click_ind = "flex"                   'Go to next step

  Next i      'NEXT FORCE STEP

OK_MAX:     'GRIP TO THE MAXIMUM FORCE

   'Switch Info window off
   form2.Visible = False

  'Reset indicators
   click_ind = ""
   Call reset_Off

   'Close the thumb and index finger
   IFB_SetRight "ab"
   IFB_Onfor "b", 5
   IFB_Onfor "a", 20
   Call wait(5)

  'Do until max force limit is reached in thumb or index finger
  'and switch motors off
    Do
    DoEvents
      thumb_current = IFB_Raw(1)
      index_current = IFB_Raw(2)
    Loop Until (thumb_current > thumb_max) Or (index_current > index_max)
      IFB_Off "ab"

   'Write Info box
   Call info_box("SELECT CONTROL SIGNAL", "EXTEND = Reset to park mode", "extend = Opens the hand", "", "", "",
"")

   'Wait for signal
    Do
     DoEvents
     If click_ind = "extend" Then GoTo OK_RELEASE   'Release object
```

```
    If click_ind = "EXTEND" Then Call Park_grip    'Release and park
   Loop Until click_ind = "EXTEND"


OK_RELEASE:     'RELEASE THE GRIP ON THE OBJECT FOR REGRIPPING
  'Reset
   click_ind = ""

  'Release grip
   IFB_SetLeft "ab"

   'Extend thumb and index finger
   IFB_Onfor "ab", 10

GoTo OK_WAIT
End Sub

Sub Side_Grip ()
   'Switch Info window off
   form2.Visible = False

   'Direction and power
   IFB_SetRight "b"
   IFB_SetLeft "ac"
   IFB_Setpower "d", 5

   'Open thumb slightly
   IFB_Onfor "a", 5

    'Flex 3-fingers then index
   IFB_Onfor "c", 10
   IFB_Onfor "b", 10

SIDE_WAIT:  'HAND STILL OPEN, WAITING FOR SIGNAL

  'Switch Info window off
   form2.Visible = False
  'Reset click indicator
   click_ind = ""
  'Write information box
   Call info_box("SELECT CONTROL SIGNAL", "FLEX = Close to max force", "flex = Close to next force step",
"EXTEND = Reset to park mode", "", "", "")

   'Wait for signal
   Do
    DoEvents
    If click_ind = "flex" Then GoTo SIDE_STEPS  'close in steps
    If click_ind = "FLEX" Then GoTo SIDE_MAX    'close to the max
    If click_ind = "EXTEND" Then Call Park_grip  'go back to park
   Loop Until a = 99


SIDE_STEPS:     'GRIP IN PRESET FORCE STEPS

   'Switch information box off
   form2.Visible = False

   'Set switch-off current for thumb
   thumb_value = thumb_stop
   index_value = index_stop

   For i = 1 To 3      'BEGIN FORCE STEP
     click_ind = ""
     Call reset_Off
```

```
  'Close the thumb only
   IFB_SetRight "a"
   IFB_Onfor "a", 30
   Call wait(5)

 'Do until force limit is reached in thumb
 'and switch motor off
   Do
   DoEvents
     thumb_current = IFB_Raw(1)
   Loop Until (thumb_current > thumb_value)
     IFB_Off "a"

    'Reset switch-off current for thumb motor
     thumb_value = thumb_value + thumb_step

  'Write information box
  Call info_box("SELECT CONTROL SIGNAL", "FLEX = Close to max force", "flex = Close to next force step",
"EXTEND = Reset to park mode", "extend = Opens the hand", "", "")

  'Wait for signal
  Do
   DoEvents
   If click_ind = "extend" Then GoTo SIDE_RELEASE  'Release object
   If click_ind = "EXTEND" Then Call Park_grip    'Release and park
   If click_ind = "FLEX" Then GoTo SIDE_MAX       'Grip to the maximum
  Loop Until click_ind = "flex"                   'Go to next step

 Next i      'NEXT FORCE STEP

SIDE_MAX:   'GRIP TO THE MAXIMUM FORCE

  'Switch Info window off
  form2.Visible = False

 'Reset indicators
  click_ind = ""
  Call reset_Off

  'Close the thumb only
   IFB_SetRight "a"
   IFB_Onfor "a", 30
   Call wait(5)

 'Do until max force limit is reached in the thumb
 'and switch motors off
   Do
   DoEvents
     thumb_current = IFB_Raw(1)
   Loop Until (thumb_current > thumb_max)
     IFB_Off "ab"

  'Write Info box
  Call info_box("SELECT CONTROL SIGNAL", "EXTEND = Reset to park mode", "extend = Opens the hand", "", "", "",
"")

  'Wait for signal
   Do
    DoEvents
    If click_ind = "extend" Then GoTo SIDE_RELEASE  'Release object
    If click_ind = "EXTEND" Then Call Park_grip    'Release and park
   Loop Until click_ind = "EXTEND"
```

```
SIDE_RELEASE:     'RELEASE THE GRIP ON THE OBJECT FOR REGRIPPING
  'Reset
   click_ind = ""

  'Release grip
   IFB_SetLeft "a"

   'Extend thumb
   IFB_Onfor "a", 10

GoTo SIDE_WAIT
End Sub

Sub Small_Grip ()
   'Switch Info window off
   form2.Visible = False

   'Direction and power
   IFB_SetRight "b"
   IFB_SetLeft "acd"
   IFB_Setpower "d", 5

    'Rotate Thumb
   IFB_Onfor "d", 20
 Do
    DoEvents
     port_bite = form1.IOPORT2.PortData
     bin_code = bin(port_bite)
 Loop Until thumb_bit110 = True
   IFB_Off "d"

   'Extend thumb
   IFB_Onfor "a", 7

    'Flex 3-fingers then index slightly
   IFB_Onfor "bc", 15

SMALL_WAIT:  'HAND STILL OPEN, WAITING FOR SIGNAL

  'Switch Info window off
   form2.Visible = False
  'Reset click indicator
   click_ind = ""
  'Write information box
   Call info_box("SELECT CONTROL SIGNAL", "FLEX = Close to max force", "flex = Close to next force step",
"EXTEND = Reset to park mode", "", "", "")

   'Wait for signal
   Do
    DoEvents
    If click_ind = "flex" Then GoTo SMALL_STEPS  'close in steps
    If click_ind = "FLEX" Then GoTo SMALL_MAX    'close to the max
    If click_ind = "EXTEND" Then Call Park_grip  'go back to park
   Loop Until a = 99


SMALL_STEPS:      'GRIP IN PRESET FORCE STEPS

   'Switch information box off
   form2.Visible = False

   'Set switch-off current for each motor
   thumb_value = thumb_stop
   index_value = index_stop
```

```
  finger_value = finger_stop

  For i = 1 To 3      'BEGIN FORCE STEP
    click_ind = ""
    Call reset_Off

  'Close all fingers
  IFB_SetRight "ab"
  IFB_SetLeft "c"
  IFB_Onfor "a", 30
'  Call wait(10)
  IFB_Onfor "bc", 40
  Call wait(5)


 'Do until force limits are reached and switch motors off
   Do
   DoEvents
     thumb_current = IFB_Raw(1)
     If thumb_current > thumb_value Then
      thumb_Off = True
      IFB_Off "a"
     End If
     index_current = IFB_Raw(2)
     If index_current > index_value Then
      IFB_Off "b"
      index_Off = True
     End If
     finger_current = IFB_Raw(3)
     If finger_current > finger_value Then
      IFB_Off "c"
      finger_Off = True
     End If
   Loop Until (thumb_Off And index_Off And finger_Off) = True
    'Reset switch-off current for each motor
     thumb_value = thumb_value + thumb_step
     index_value = index_value + index_step
     finger_value = finger_value + finger_step

   'Write information box
   Call info_box("SELECT CONTROL SIGNAL", "FLEX = Close to max force", "flex = Close to next force step",
"EXTEND = Reset to park mode", "extend = Opens the hand", "", "")

   'Wait for signal
   Do
    DoEvents
    If click_ind = "extend" Then GoTo SMALL_RELEASE 'Release object
    If click_ind = "EXTEND" Then Call Park_grip    'Release and park
    If click_ind = "FLEX" Then GoTo SMALL_MAX      'Grip to the maximum
   Loop Until click_ind = "flex"                   'Go to next step

  Next i         'NEXT FORCE STEP

SMALL_MAX:     'GRIP TO THE MAXIMUM FORCE

   'Switch Info window off
   form2.Visible = False

  'Reset indicators
   click_ind = ""
   Call reset_Off

   'Close all fingers
   IFB_SetRight "ab"
```

```
    IFB_SetLeft "c"
    IFB_Onfor "a", 30
'    Call wait(10)
    IFB_Onfor "bc", 40
    Call wait(5)

   'Do until force limits are reached and switch motors off
    Do
     DoEvents
      thumb_current = IFB_Raw(1)
      If thumb_current > thumb_max Then
       thumb_Off = True
       IFB_Off "a"
      End If
      index_current = IFB_Raw(2)
      If index_current > index_max Then
       IFB_Off "b"
       index_Off = True
      End If
      finger_current = IFB_Raw(3)
      If finger_current > finger_max Then
       IFB_Off "c"
       finger_Off = True
      End If
    Loop Until (thumb_Off And index_Off And finger_Off) = True

    'Write Info box
    Call info_box("SELECT CONTROL SIGNAL", "EXTEND = Reset to park mode", "extend = Opens the hand", "", "", "",
"")

    'Wait for signal
     Do
      DoEvents
      If click_ind = "extend" Then GoTo SMALL_RELEASE 'Release object
      If click_ind = "EXTEND" Then Call Park_grip     'Release and park
     Loop Until click_ind = "EXTEND"



SMALL_RELEASE:      'RELEASE THE GRIP ON THE OBJECT FOR REGRIPPING
   'Reset
    click_ind = ""

   'Release grip
    IFB_SetLeft "ab"
    IFB_SetRight "c"

    'Extend thumb first
    IFB_Onfor "a", 15

    'Extend other fingers
    IFB_Onfor "bc", 5

GoTo SMALL_WAIT
End Sub

Sub Sphere_Grip ()
    'Switch Info window off
    form2.Visible = False

    'Direction and power
    IFB_SetRight "be"
    IFB_SetLeft "acd"
    IFB_Setpower "d", 5
```

```
    'Rotate Thumb
   IFB_Onfor "d", 20
  Do
    DoEvents
     port_bite = form1.IOPORT2.PortData
     bin_code = bin(port_bite)
  Loop Until thumb_bit110 = True
   IFB_Off "d"

    'Flex 3-fingers then index slightly
   IFB_Onfor "bce", 7

    'Extend thumb
   IFB_Onfor "a", 10

SPHERE_WAIT:  'HAND STILL OPEN, WAITING FOR SIGNAL

  'Switch Info window off
   form2.Visible = False
  'Reset click indicator
   click_ind = ""
  'Write information box
   Call info_box("SELECT CONTROL SIGNAL", "FLEX = Close to max force", "flex = Close to next force step",
"EXTEND = Reset to park mode", "", "", "")

   'Wait for signal
   Do
    DoEvents
    If click_ind = "flex" Then GoTo SPHERE_STEPS  'close in steps
    If click_ind = "FLEX" Then GoTo SPHERE_MAX    'close to the max
    If click_ind = "EXTEND" Then Call Park_grip  'go back to park
   Loop Until a = 99


SPHERE_STEPS:     'GRIP IN PRESET FORCE STEPS

   'Switch information box off
   form2.Visible = False

   'Set switch-off current for each motor
   thumb_value = thumb_stop
   index_value = index_stop
   finger_value = finger_stop

   For i = 1 To 3      'BEGIN FORCE STEP
     click_ind = ""
     Call reset_Off

   'Close all the fingers
    IFB_SetRight "ab"
    IFB_SetLeft "c"
    IFB_Onfor "abc", 30
    Call wait(5)

   'Do until force limits are reached and switch motors off
    Do
    DoEvents
     thumb_current = IFB_Raw(1)
     If thumb_current > thumb_value Then
      thumb_Off = True
      IFB_Off "a"
     End If
     index_current = IFB_Raw(2)
```

```
      If index_current > index_value Then
       IFB_Off "b"
       index_Off = True
      End If
      finger_current = IFB_Raw(3)
      If finger_current > finger_value Then
       IFB_Off "c"
       finger_Off = True
      End If
    Loop Until (thumb_Off And index_Off And finger_Off) = True
     'Reset switch-off current for each motor
      thumb_value = thumb_value + thumb_step
      index_value = index_value + index_step
      finger_value = finger_value + finger_step

   'Write information box
   Call info_box("SELECT CONTROL SIGNAL", "FLEX = Close to max force", "flex = Close to next force step",
"EXTEND = Reset to park mode", "extend = Opens the hand", "", "")

   'Wait for signal
   Do
     DoEvents
     If click_ind = "extend" Then GoTo SPHERE_RELEASE 'Release object
     If click_ind = "EXTEND" Then Call Park_grip      'Release and park
     If click_ind = "FLEX" Then GoTo SPHERE_MAX       'Grip to the maximum
   Loop Until click_ind = "flex"                  'Go to next step

   Next i            'NEXT FORCE STEP

SPHERE_MAX:     'GRIP TO THE MAXIMUM FORCE

    'Switch Info window off
    form2.Visible = False

   'Reset indicators
    click_ind = ""
    Call reset_Off

    'Close all the fingers
      IFB_SetRight "ab"
      IFB_SetLeft "c"
      IFB_Onfor "abc", 30
      Call wait(5)

   'Do until force limits are reached and switch motors off
     Do
      DoEvents
        thumb_current = IFB_Raw(1)
        If thumb_current > thumb_max Then
         thumb_Off = True
         IFB_Off "a"
        End If
        index_current = IFB_Raw(2)
        If index_current > index_max Then
         IFB_Off "b"
         index_Off = True
        End If
        finger_current = IFB_Raw(3)
        If finger_current > finger_max Then
         IFB_Off "c"
         finger_Off = True
        End If
      Loop Until (thumb_Off And index_Off And finger_Off) = True
```

```
   'Write Info box
   Call info_box("SELECT CONTROL SIGNAL", "EXTEND = Reset to park mode", "extend = Opens the hand", "", "", "", "")

   'Wait for signal
    Do
     DoEvents
     If click_ind = "extend" Then GoTo SPHERE_RELEASE 'Release object
     If click_ind = "EXTEND" Then Call Park_grip      'Release and park
    Loop Until click_ind = "EXTEND"


SPHERE_RELEASE:     'RELEASE THE GRIP ON THE OBJECT FOR REGRIPPING
   'Reset
    click_ind = ""

   'Release grip
    IFB_SetLeft "ab"
    IFB_SetRight "c"

    'Extend all fingers
    IFB_Onfor "abc", 7

GoTo SPHERE_WAIT
End Sub

Sub Tip_Grip ()
    'Switch Info window off
    form2.Visible = False

    'Direction and power
    IFB_SetRight "b"
    IFB_SetLeft "acd"
    IFB_Setpower "d", 5

     'Rotate Thumb
    IFB_Onfor "d", 20
   Do
     DoEvents
      port_bite = form1.IOPORT2.PortData
      bin_code = bin(port_bite)
   Loop Until thumb_bit110 = True
    IFB_Off "d"

     'Flex 3-fingers then index
    IFB_Onfor "c", 10
    IFB_Onfor "b", 12

    'Open thumb slightly
    IFB_Onfor "a", 5

 TIP_WAIT:  'HAND STILL OPEN, WAITING FOR SIGNAL

    'Switch Info window off
     form2.Visible = False
    'Reset click indicator
     click_ind = ""
    'Write information box
     Call info_box("SELECT CONTROL SIGNAL", "FLEX = Close to max force", "flex = Close to next force step", "EXTEND = Reset to park mode", "", "", "")

     'Wait for signal
     Do
      DoEvents
```

```
   If click_ind = "flex" Then GoTo TIP_STEPS 'close in steps
   If click_ind = "FLEX" Then GoTo TIP_MAX   'close to the max
   If click_ind = "EXTEND" Then Call Park_grip 'go back to park
  Loop Until a = 99


TIP_STEPS:     'GRIP IN PRESET FORCE STEPS

  'Switch information box off
  form2.Visible = False


  'Set switch-off current for thumb
  thumb_value = thumb_stop
  index_value = index_stop

  For i = 1 To 3     'BEGIN FORCE STEP
    click_ind = ""
    Call reset_Off

  'Close the thumb only
   IFB_SetRight "a"
   IFB_Onfor "a", 10
   Call wait(1)

  'Do until force limit is reached in thumb
  'and switch motor off
   Do
   DoEvents
     thumb_current = IFB_Raw(1)
   Loop Until (thumb_current > thumb_value)
     IFB_Off "a"

    'Reset switch-off current for thumb motor
     thumb_value = thumb_value + thumb_step

  'Write information box
  Call info_box("SELECT CONTROL SIGNAL", "FLEX = Close to max force", "flex = Close to next force step",
"EXTEND = Reset to park mode", "extend = Opens the hand", "", "")

  'Wait for signal
  Do
   DoEvents
   If click_ind = "extend" Then GoTo TIP_RELEASE 'Release object
   If click_ind = "EXTEND" Then Call Park_grip    'Release and park
   If click_ind = "FLEX" Then GoTo TIP_MAX        'Grip to the maximum
  Loop Until click_ind = "flex"                  'Go to next step

  Next i     'NEXT FORCE STEP

TIP_MAX:   'GRIP TO THE MAXIMUM FORCE

  'Switch Info window off
  form2.Visible = False

  'Reset indicators
   click_ind = ""
   Call reset_Off

  'Close the thumb only
   IFB_SetRight "a"
   IFB_Onfor "a", 10
   Call wait(5)
```

```
  'Do until max force limit is reached in the thumb
  'and switch motors off
    Do
    DoEvents
     thumb_current = IFB_Raw(1)
    Loop Until (thumb_current > thumb_max)
     IFB_Off "ab"

   'Write Info box
   Call info_box("SELECT CONTROL SIGNAL", "EXTEND = Reset to park mode", "extend = Opens the hand", "", "", "", "")

   'Wait for signal
    Do
     DoEvents
     If click_ind = "extend" Then GoTo TIP_RELEASE  'Release object
     If click_ind = "EXTEND" Then Call Park_grip     'Release and park
    Loop Until click_ind = "EXTEND"



TIP_RELEASE:     'RELEASE THE GRIP ON THE OBJECT FOR REGRIPPING
  'Reset
   click_ind = ""

  'Release grip
   IFB_SetLeft "a"

   'Extend thumb
   IFB_Onfor "a", 10

GoTo TIP_WAIT
End Sub

Sub Park_grip ()
   'Switch Info window off
   form2.Visible = False

   'If hand is already parked go to the end
   If PARK = True Then GoTo PARKED

   'Reset Off-indicators
      click_ind = ""
      Call reset_Off

   'Set power and directions
   IFB_Setpower "d", 5
   IFB_SetLeft "abe"
   IFB_SetRight "cd"
    port_bite = form1.IOPORT2.PortData
    bin_code = bin(port_bite)

   'Open thumb if flexed open it first
  If ext_bit1 = False Then
   IFB_Onfor "a", 50
   Call wait(1)
  End If

   IFB_Onfor "b", 45
   IFB_Onfor "c", 45
   IFB_Onfor "e", 10
   IFB_Onfor "d", 45
   count = 0
```

```
Do
   DoEvents
    port_bite = form1.IOPORT2.PortData
    bin_code = bin(port_bite)

  If (ext_bit2 = True) And (index_Off = False) Then
    IFB_Off "b"
    index_Off = True
  End If
  If ((ext_bit3 Or ext_bit4 Or ext_bit5) = True) And (finger_Off = False) Then
    IFB_Off "c"
    finger_Off = True
  End If
  If (thumb_bit0 = True) And (oppose_Off = False) Then
    IFB_Off "d"
    oppose_Off = True
  End If
  If (ext_bit1 = True) And (thumb_Off = False) Then
    IFB_Off "a"
    thumb_Off = True
  End If
Loop Until ((thumb_Off And index_Off And finger_Off And oppose_Off) = True)
  IFB_Off "abcd"

  Call wait(5)
  IFB_SetRight "a"
  IFB_Onfor "a", 10

PARKED:

  'Reset park indicator
  PARK = False

  'Write message
  Call info_box("", "", "PRESS 'BOTH' TO START", "", "", "", "")

  'Wait for initiation signal
  Do
    DoEvents
  Loop Until click_ind = "BOTH"
  form2.Visible = False

  Call MODE_SELECTION
End Sub
```

B.3.2 Local declarations (*.frm)

B.3.3 Help (hand.txt)

UCT - PROSTHETIC HAND

Developed by: Johan Kotze (1996)

HELP FILE

1.
GENERAL INFORMATION

The UCT-hand was originally designed to be used as a
prosthetic hand. Due to the complex nature of the

contol of a prosthetic hand two separate control strategies were devised to accommodate different levels of users.

"The first mode is the MANUAL control, for beginners" or children. In this mode each motor can be controlled individually. The other option is the "AUTOMATIC mode, for more advanced users. This" control of the hand is the same as it would be for a dextrous prosthetic hand using two input signals.

"For operation, follow the instuctions given by the" active window or the information windows. For additional information refer to the help page for each active screen.

"NOTE: Dear user, please keep in mind that the hand" is a fragile peace of equipment. Do not try to force it manually in any way. If something goes wrong use the 'stop' button and reset the hand. If the error occurred in the AUTOMATIC mode switch to the MANUAL mode manually control individual fingers. "If nothing works, exit the program and try again ."

2.

AUTOMATIC CONTROL

The automatic control is symilar to that of a real "prosthetic hand, where the control signals is supplied" by two electro myoghraphic(EMG) signals from contractions of antagonistic mucle groups. The control consists of variations in the combinations and durations of these signals. The two muscles can be contacted sepearaty or simmultaneously. The contactions can also be instantaneuos or for a slight duration. All these variations provides a total of 6 signals to control the hand. These signals are used in the most natural way possible to reduce the mental load on the user. The signals are used to select various preprogrammed hand shapes and then to grip and release the object.

There are 9 basic hand shapes. The resting position is called 'Park'. The hand returns to this position when it is reset or switched on and after you're finshed using any handshape was used and fully extended afterwards. An information window will gide you through the gripping procedure. The remaining 8 shapes are devided into two modes:

" CYLINDER MODE - Large, Small, Sphere, Side"
" INDEX MODE - Needle, OK, Chuck, Tip"

3.

MANUAL CONTROL

Manual control provide a very easy and direct way of controlling the hand. There are two buttons for each motor. Each button run them motor in an opposite direction. The 'Stop' button stops all the motors. The motors will also stop closing when the forces in the fingers are too big and stop opening when fully opened. The thumb rotates until the limits are reached.

This window can also be used to correct the errors ocuuring in the hand.

4.

Automatic Operation

Signals are presented by three buttons:

" Flex - Contraction of flexor muscle"
" Extend - Contraction of extensor muscle"
" Both - Simmultaneous mucle contraction"

"'Clicking' the button represents a short muscle contration," while 'holding' it down for longer than half second represents a longer contraction.

The information window indicated the click of a button in small letters ('flex') and the held down of a button in capital letters ('FLEX').

To start click on the 'Reset/start' button. This will return the hand to the 'Parked state' at all times. The information "window will guide you as you select the MODES, then" select the "HAND SHAPES and then GRIPPING and RELEASING the object.

"The 'Stop - All' button stops all the motors in case of an" emergency. If resetting the hand does not correct the error switch to the manual window and try to correct it manually with the help of the 'Test sensors' button.

5.

Manual Operation

There are five motors and therefore 5 functions to control.
" MOTOR A - open/close the thumb"
" MOTOR B - open/close the index finger"
" MOTOR C - open/close the last three fingers simultaneously"
" MOTOR D - rotates the thumb towards the middel of the hand"
" MOTOR E - moves the fingers sideways, away from each other"

"If something is not working the way it is supposed to, use the" 'Test sensors' button. This switch on a window which shows the values of all the limit switches and and force sensors. The limit sensors are equal to '-1' when the finger is fully opened or a limit is reached and equal to '0' when somewhere in between. The force sensors represents a relative value for the motor current in the three flexor motors. This value is proportional to the torque supplied by each motor and and therefore the force in the finger. These can be used to see if all the sensors are working properly or to correct something that went wrong. While this window appears the control of the hand change so that it is fully manual and do not switch off by itself.

NOTE: Always make sure all the controls are plgged in swithed on and properly connected. If a finger are closing when they should be opening or the other way around push the 'Test sensors' button and then the 'close' button until it change to the right direction. Make sure the limit switch it clean.

6.
Sensors

This window displays the different sensor inputs. This can be used to show the principle of how the hand feedback works or to test if all the sensors are working properly. The sensors detecting finger postion are binary contact switches and are quite fragile. They should be checked and cleaned regularly.

There are 3 frames:

```
"  Finger open     - shows when each finger is fully opened"
"  Thumb rotation - shows the thumb position in degrees as"
"                     it rotates (fully opposed is 110 degrees)"
"  Motor forces    - shows the current in 3 motors which is"
"                    relative to the forces applied by them."
"                    (It only works when motors are closing.)"
```

The first two frames are binary windows with:

```
"  contact    = -1"
"  no contact =  0"
```

The last frame just give a relative analogue value representing the force in the 3 flexor motors.

APPENDIX C

CIRCUITRY AND CONNECTIONS

C.1 Developed circuitry

The PC-14 digital card needs a 5V signal as an input signal. The card is used to detect closure of the limit switches. A 5V potential is therefore needed at all the limit switches. The potential is supplied by the PC-14 card. The circuitry developed to supply this potential to all the limit switches is presented in Figure C-1. The circuitry provide an output to the card for each limit switch which has a 0V potential when closed and 5V potential when open. This signal is inverted by the software to provide a “true” signal when the switch is closed and a “false” signal when open.

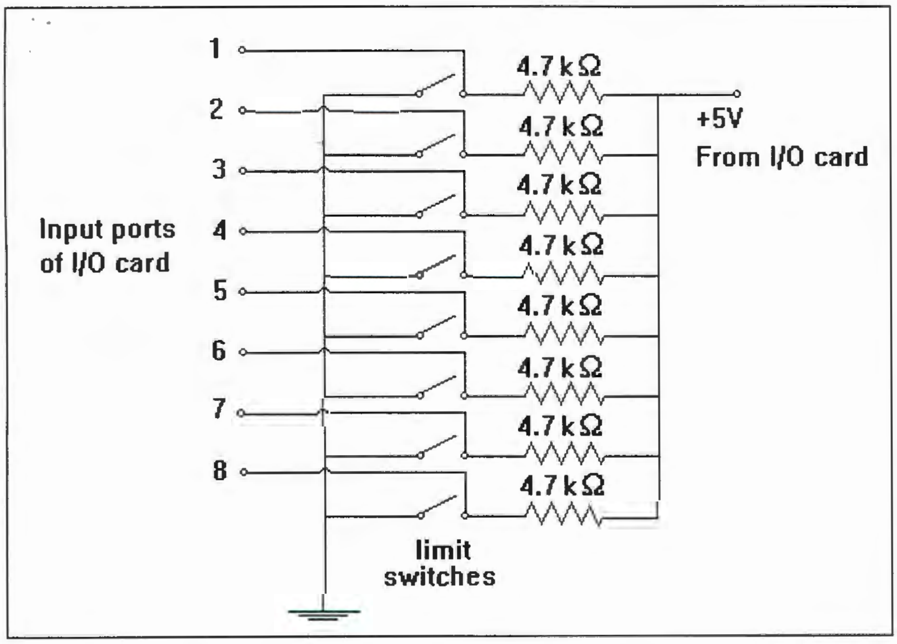

Figure C-1: The circuitry providing an input to the PC-14 card.

C.2 Connectors

UCT-box is connected to the hand using computer ribbon cable which plugs into a 40 pin connector on the top of the hand. The pin connection to the connector is shown in Figure C-2(a). The UCT-box is connected to the PC-14 card using a ribbon cable and a 40 pin connector. The pin connections are presented in Figure C-2(b).

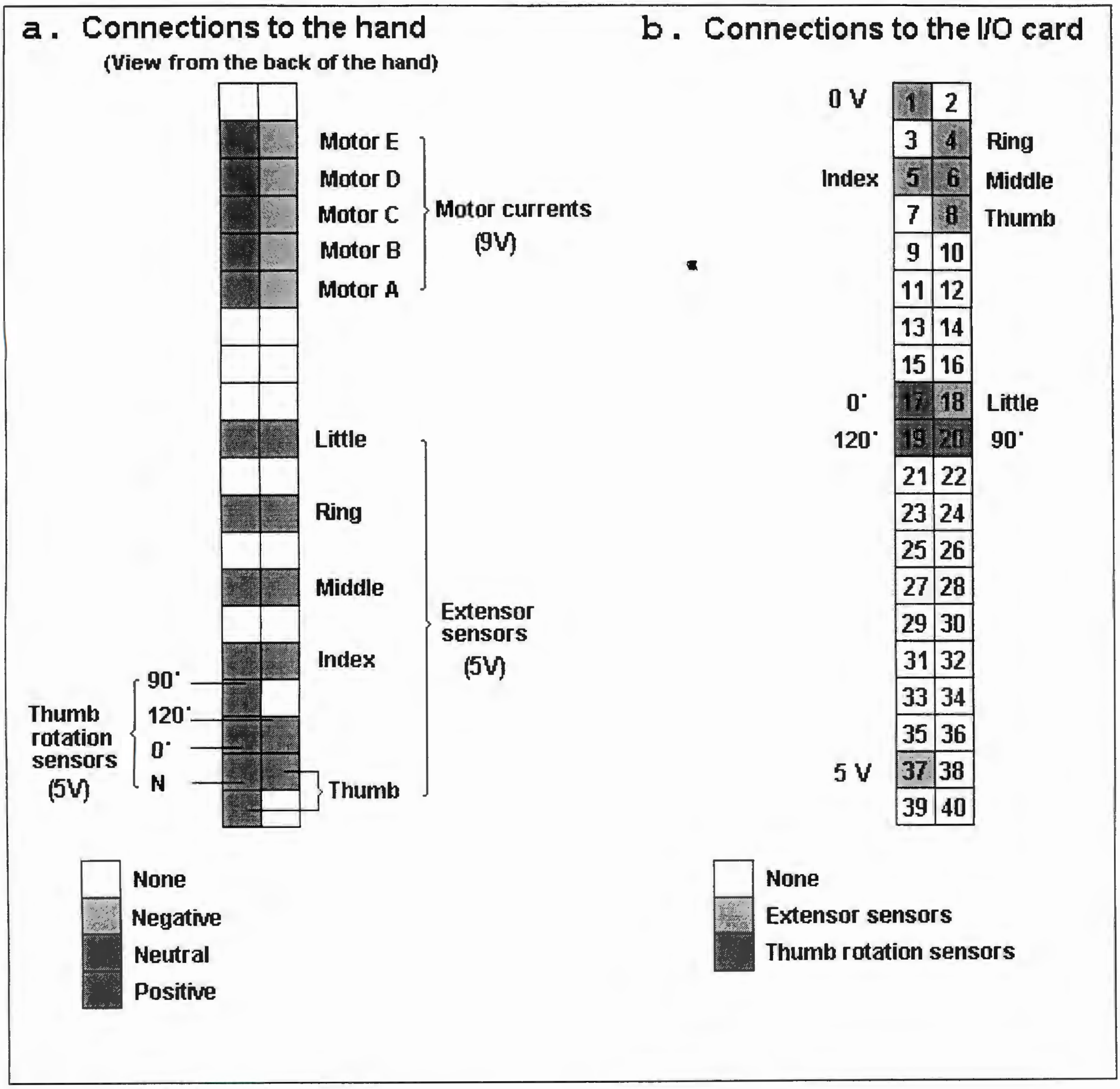

Figure C-2: Cable connections of the hand.