Towards a Universal End Effector: The Design and Development of Production Technology's Intelligent Robot Hand

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Abstract

Research into robot hands for industrial use began in the early 1980s and there are now many examples of robot hands in existence. The reason for research into robot hands is that standard robot end effectors have to be designed for each application and are therefore costly. A universal end effector is needed that will be able to perform any parts handling operation or use other tools for other industrial operations. Existing robot hand research would therefore benefit from new concepts, designs and control systems.

The Department of Production Technology is developing an intelligent robot hand of a novel configuration, with the ultimate aim of producing a universal end effector. The concept of PTIRH (Production Technology's Intelligent Robot Hand) is that it is a multi-fingered manipulator with a configuration of two thumbs and two fingers.

Research by the author for this thesis concentrated on five major areas. First, the background research into the state of the art in robot hand research. Second, the initiation, development and analysis of the novel configuration concept of PTIRH. Third, specification, testing and analysis of air muscle actuation, including design, development and testing of a servo pneumatic control valve for the air muscles. Fourth, choice of sensors for the robot hand, including testing and analysis of two custom made air pressure sensors. Fifth, definition, design, construction, development, testing and analysis of the mechanical structure for an early prototype of PTIRH. Development of an intelligent controller for PTIRH was outside the scope of the author's research.

The results of the analysis on the air muscles showed that they could be a suitable direct drive actuator for an intelligent robotic hand. The force, pressure and position sensor results indicate that the sensors could form the basis of the feedback loop for an intelligent controller. The configuration of PTIRH enables it to grasp objects with little reliance on friction. This was demonstrated with an early prototype of the robot hand, which had one finger with actuation and three other static digits, by successfully manually arranging the digits into stable grasps of various objects.

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Author's Publication

The following publication was prepared during research for this thesis:

Harris, M.T. & Nahavandi, S., *Design and Development of an Intelligent Robotic Hand,* Proceedings of the 2nd New Zealand Postgraduate Conference for Engineering and Technology Students, Auckland University, New Zealand, pp. 119-124, August 1995.

Chapter 1

INTRODUCTION

1.1 Topic of Research

The robot hand project which is being undertaken in the Department of Production Technology at Massey University is known as PTIRH (Production Technology's Intelligent Robot Hand). PTIRH is intended to be a major step forward towards universal end effectors for robots and to be able to perform small assembly and material manipulation operations.

The research undertaken by the author is concerned with the design and development of the mechanical robot hand, which is to be a step towards a universal robot hand. A robot hand is a multi-fingered manipulator for a robot. The human hand is a successful design for a multi-fingered manipulator and so examination of the human hand is important in the design of robot hands. The dexterity of a robot hand comes from considering dexterity issues in the design of the mechanical structure and the intelligent control system.

The development of a universal robot hand is becoming essential for applications in which changes in robot arm end effectors are undesirable. Space exploration is one field where it is important that a single end effector be able to grasp and manipulate any object deemed necessary [1]. In the factory, time spent changing end effectors can delay an automated process and a single universal gripper could be of lower cost than many specialised end effector manipulators. Ideally a single end effector would be able to perform every operation required of the robot system. Instead of being just a complicated tool on the end of the robot arm, the end effector should be capable of using other tools. Salisbury [2] states that robot hands can be used to extend manipulation capability in terms of cost effectiveness and in terms of the overall complexity of tasks that may be performed.

PTIRH will use a novel form of actuator for robot hands which the author believes to have advantages over the DC electric motors and pulley systems approach of other robot hands.

The hand configuration is two thumbs and two fingers. No other hands of this configuration have been found in an exhaustive search of the literature. Two thumbs will be advantageous in grasping and manipulating due to the lesser reliance on friction to maintain the grasp. This will enable the grasp and manipulation control system to be simpler, possibly at the expense of a more complex control system for moving the extra thumb.

1.2 Scope of Research

The research reported here concerns the development of a robot hand that is to be a step towards a universal end effector. In particular, this thesis reports on the processes involved with the design of the mechanical robot hand, the implementation of the design and testing of the design. The development of an intelligent controller is outside the scope of this research.

Robot hands to date have suffered from limitations imposed by their mechanical design and availability of actuators. To achieve a robot hand which avoids the limitations of other robot hands, two novel concepts were proposed. These were: the use of a non-anthropomorphic configuration of PTIRH and the use of novel pneumatic 'air muscle' actuators. Through the use of these two concepts in the design of the robot hand and integrating sensors in to the design of the hand, a mechanical hand will be constructed to enable research and development in the area of an intelligent control system for the hand.

Research in both concept areas was to follow a planned development cycle of design, implementation and testing. The aim of the design phase consisted of firstly investigating the topic and secondly developing specifications. The implementation phase was concerned with taking the specifications and implementing them on a prototype.

It was realised early on in the research that construction and testing of an entire robot hand was constrained by time. Therefore the area of the non-anthropomorphic configuration of an entire hand was confined to design, with a single prototype finger being constructed for testing. An early prototype of the robot hand was constructed which will include the prototype finger and three other digits without actuation. Testing will occur on the components of the finger and the concepts behind the two thumb, two finger robot hand configuration.

1.3 Structure of Thesis

The research and development for this work takes the project from the literature review, feasibility study and design concept stage through the design and development stage and up to the testing of the prototype robot hand and the analysis of the concept of PTIRH. The structure of this thesis reflects this design process.

Chapter One provides an introduction and scope for the research. Reasons for research and development into robot hands are given with an emphasis on the definition of intelligent robotics.

Chapter Two reviews the literature on robot hands and relevant background topics to robot hand research. As robotics is a bringing together of many different types of technologies and skills, so too is robot hand research, with an added emphasis on human hand physiology. The state of the art is examined, with a particular emphasis on learning from the successes and avoiding the problems.

In chapter Three the design goals for Production Technology's Intelligent Robot Hand are given. The reasons for the choice of sensors and air muscle actuators are given. The design of a servo pneumatic valve to use with the air muscles is explored. The mechanical design process for PTIRH is described and a final design chosen. The implementation of the design into a prototype robot finger and an early prototype robot hand is discussed.

Chapter Four evaluates the results of testing on the prototype intelligent robot finger and gives the analysis of the PTIRH concept. The success of the robot finger is discussed, along with the servo pneumatic valve, the air muscles and sensors. The prototype hand is used to demonstrate grasps possible with the two thumb, two finger configuration.

Chapter Five concludes the thesis.

Chapter Six has suggestions for future work in the research and development of intelligent robot hands in the Department of Production Technology at Massey University.

Relevant experimental data and design drawings for the hand are included in the appendices.

1.4 The Reasoning Behind Building Robot Hands

As robotic systems become integrated into flexible manufacturing systems there is a need for robots to become more universal in their application. In order for the true flexibility of robots to be realised, end effectors need to become less of a tool to do one particular operation and more of a device to use a tool. Other applications have a need for universal robotics also. NASA has identified that remote dexterous manipulators are critical to the successful maintenance of space stations [1].

A common universal end effector design is anthropomorphic in nature, although other configurations have been proposed. In the Production Technology Department at Massey University design and development is proceeding on an intelligent robot hand that will be able to perform many different functions. This intelligent robot hand will have a configuration of two fingers and two thumbs.

An intelligent robot hand is a step towards a universal end effector for a robot arm that has the same functions as a human hand (often resembling a human hand) and can grasp and manipulate objects in a manner similar to a human hand. An intelligent robot hand is part of a closed loop with its controller and has sensors to give information to the controller. An intelligent robot hand is intended to be as universal as possible so it can be used for any task with little or no reprogramming, understanding the change in task through feedback from sensors. The intelligence of a robot can also reduce the need for other equipment, such as part orientation guides, or controllers in a robotic work cell [3].

Intelligent control systems for robots can take a programmed motion and alter it in response to environmental conditions in the work place [4]. Intelligent robots can communicate with their operators or other computer-based systems, integrate and fuse information from sensors and model their environment. The ultimate intelligent robot would be able to repair itself. At the current state of the art, the level of intelligence of intelligent robots is primitive at best but will improve with advances in micro-actuators, parallel processors and smart sensors. Even the addition of a simple sensor and a control system to use the feedback can make a robot manipulator more intelligent than one without the sensor and control system.

There are three basic reasons [5] for utilising intelligent robots:

1. Technical - improving the quality of the product, reducing the waste from the process and increasing flexibility in the process.
2. Economic - cost benefits of robots that can work non-stop, which result in improved utilisation of other equipment and the freeing up of trained people for jobs which can not be done by robots.
3. Social - taking humans out of jobs that are dangerous, unhealthy, boring and arduous.

Sixty percent of parts in robotic assembly can be handled by manipulators with two fingers. Another twenty five percent can be handled by three fingered manipulators and the remaining parts require handling by four or more fingers [6, 7]. Therefore it is concluded that a manipulator based on a human hand, "the finest machine ever created" [8], will be able to handle all parts involved in robotic assembly.

Current robot hands of four or five digits are considered by some researchers not to be suitable for assembly operations because of their slow movement, low reliability and bad positioning accuracy[9]. However, other researchers say that more fingers will be an advantage. Jacobsen et al [10] believe a greater number of fingers results in even more versatile hand designs, finger redundancy permits more flexibility in grasping and manipulations are easier. Tanie [11] holds that increasing the number of fingers up to a maximum of five will allow the capability to accommodate change in object shapes. Alexander [12] believes that with more than five fingers even more complex tasks than those already possible could be performed. Any multi-fingered robot hand will certainly need to be fast moving, reliable and accurate, while taking advantage of the redundancy and grasp options available with more fingers.

The human hand is very versatile; as well as being a powerful tool itself, it is able to use an almost unlimited range of other tools. Some researchers [13, 14] consider this a disadvantage in robotics, believing that a multi-finger approach will complicate the assembly process, be expensive and that it would be a mistake to assume the human hand is the ideal gripper as the manufacturing world is much more restricted than the one for which the human hand is designed. They point out that the human hand often has to use pliers, tweezers or gloves to be able to pick up certain objects.

There is no doubt that a multi-fingered manipulator will be more complicated, and hence costly, than the standard two jaw grippers. That the manufacturing world is a subset of the human hand world is no problem, rather an advantage, as the world view needed for a robot hand is therefore reduced. The present two fingered robot grips could be compared to a person using only pliers to do every task.

The human hand makes a good starting point to begin to build more versatile, universal grippers. The 27 degrees-of-freedom a human arm and hand have are matched by state of the art hands connected to state of the art robot arms. However, the number of grasps and manipulations, and the variations, that the human hand can perform is impressive and can not begin to be matched by the robot hands of today. The grip most often used by robots at present is a simple pinch and the opposition found in a human hand is one of its most important features. Any robot hand must include this ability.

There is no reason why the human hand could not be improved upon. For example instead of fingernails, screwdriver blades could be installed - people sometimes use their fingernails as screwdrivers which can result in a broken nail. The Utah/MIT Dextrous Hand project researchers are considering mounting the thumb centrally on their hand so that the hand could become right or left handed with a shift of the thumb. It should also be possible to control a hand so that it can perform grasps and manipulations unlike those of a human.

As well as the control challenges associated with having multiple robot limbs interacting together, the development of robot hands helps with understanding in areas of intelligent sensors, the development of tactile sensors, the effect of different hand configurations and how the various components of an intelligent hand work together to produce an optimum universal robot hand.

Much work has been carried out on anthropomorphic grippers. The reasons for this are simple. Firstly, all researchers have extensive experience with their own hands to compare with the robot hand performance. Secondly, the natural human hand provides proof that an anthropomorphic geometry, properly controlled, can perform many useful grasps and manipulations, as well as providing a means of communication. Thirdly, as well as being used as robot end effectors, anthropomorphic grippers are being used as prosthetic hands. However, with prosthetics form and appearance is often more important than function.

The intention here at the Department of Production Technology is to make a hand similar to the human hand in strength, speed, usefulness, dexterity, accuracy, range of motion, controllability and sensitivity.

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Chapter 2

Review of Literature and Background to Robot Hand Research

2.1 Introduction

This chapter gives the background on the present research into robot hands. Robot hand research is the fusing of a multitude of disciplines, including engineering, metallurgy, economics, electronics, computing, physiology, micro-actuation and tactile sensing to name a selection.

Section two discusses the physiology of the human hand and seeks to discover how the human hand is constructed to meet the challenges it overcomes every day.

Section three outlines the grasps and manipulations of which the human hand is capable and extracts the grasps and manipulations of which a robot hand must be capable.

Section four is a background to the subject of robot manipulators. This section outlines the problems with current robot manipulators which research into robot hands all over the world is attempting to overcome.

Section five discusses the state of the art of the present day in robot hands. Many different hands are discussed and the good and bad points of each hand given. From this it will be possible to determine what successful design features to include in PTIRH and what problems to avoid.

Section six contains the conclusions gained from the investigation into human hand physiology, grasps and manipulations, and other researchers' robot hands.

2.2 Human Hand Physiology

2.2.1 Introduction

As well as being used to hold and manipulate objects, human hands are also part of our communication system, which complicates attempts to imitate the control system of the human hand. The structure of the hand arose because of its function and the function of the hand is a result of a process of natural selection or great design, depending upon your beliefs. Napier [1] believes the hand has an advantage over the eye, as the hand can observe and then immediately proceed to do something about what it has observed, whereas the eye has to call upon the hand. The hand can also see round corners, in the dark and is situated at the end of long, highly flexible arms that allow the sensory and motor activities to function at some distance from the brain. A point Napier stresses is that the hand itself is very primitive, but it is connected to a very powerful and complicated controller, the brain. As the human hand, along with its controller, is such an amazing mechanism it would seem sensible to examine its construction closely in order to aid the design of PTIRH.

This conclusion is supported by Klatzky and Lederman [2] who approach 'The Intelligent Hand' from a psychology perspective, and discuss the way the brain uses the information the hand sends it. They also refer to robot hands using haptic perception as a way of gathering information. Haptics includes skin sensors, giving vibratory, temperature and pressure information, and mechanoreceptors in joints, tendons and muscles, giving position and movement information [3].

Proximal and distal are two general anatomical terms describing the human hand which describe the relative position of two bones to each other. Proximal is the nearer of the two to the centre of the body, while distal is further away.

This section covers: bone structure, types of joints, muscle and tendon configuration, types of nerves, finger nail structure and composition of the skin on and in the human hand.

Human hands are very individual. Generalisations can be made about people's hands in different professions, but a person with short stumpy fingers can still be a wonderful concert pianist. This implies the brain has worked overtime to compensate for not having the extra reach and flexibility most concert pianists have. The skill of the hand lies in the brain. However, a broad stubby muscular hand is at an advantage at pick and shovel work where an extensive gripping surface is an advantage.

2.2.2 Bone Structure

The hand is made up of the wrist (eight small carpal bones), the palm (five metacarpals) and the fingers (fourteen phalanges). There are four fingers and one thumb with a total of 20 degrees-of-freedom. The fingertip bone is known as the distal phalanx and the proximal phalanx is the finger bone closest to the palm. Figure 2-1 shows the bones of the human hand.

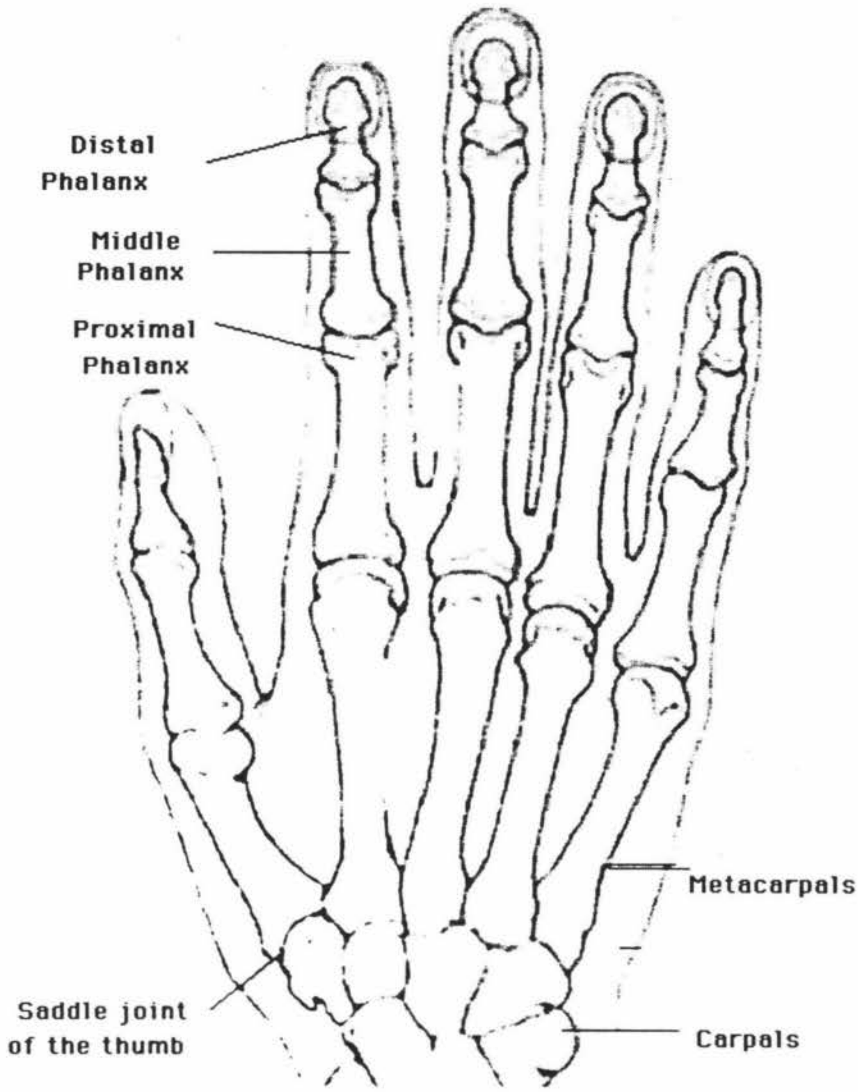

Figure 2-1: Bones of the human hand. Adapted from [4].

Primate hands are compared by using a phalangeal index, which is the ratio of the finger length to thumb length. The index represents a rationale that the longer the fingers the greater is the capacity for grasping. To a certain extent this may be true, but very long fingers would only get in the way.

2.2.3 Joint Types

The synovial joint is the most common joint in the human body and not surprisingly all 27 bones in the human hand articulate with at least one other bone using a synovial joint. Figure 2-2 shows a diagram of the synovial joint. Synovial joints are classified by the types of movement permitted. The different types of movement are hinge and pivot, bi-axial (condyloid), poly-axial (ball-and-socket), saddle (combined ball-and-socket and bi-axial) and plane.

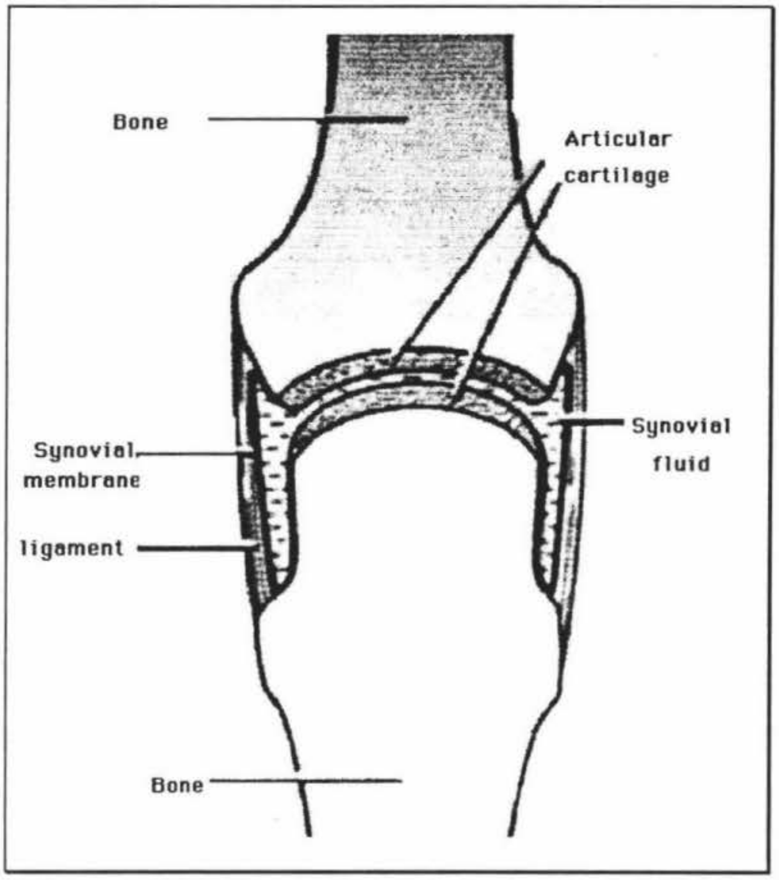

Figure 2-2: The synovial joint. Adapted from [4].

The hand has hinge joints (phalanges articulating with each other), bi-axial joints (phalanges articulating with metacarpals), a saddle joint (the thumb metacarpal articulating with the trapezium carpal bone) and plane joints (carpals articulating with each other).

All the bi-axial joints have a small amount of rotation and this is very important for opposition movements. Adduction and abduction are the name of two particular joint movements, with adduction being the movement towards an imaginary line drawn through the middle of the middle finger and movement away from it being abduction. Bending of the fingers is also known as flexion and straightening as extension.

Each finger has four degrees-of-freedom, which allows a range of finger positions and provides redundancy in positioning, giving a total of twenty degrees-of-freedom for all four fingers and the thumb.

The saddle joint of the thumb is a very unusual joint, compared to every other joint in the human body. It is a saddle joint, as described above, and interacts directly with the carpal bones of the wrist. This enables the thumb to have a range of movement and to fully oppose the fingers. Without this joint the thumb would be just another finger. The thumb has sometimes been called the lesser hand, and Sir Isaac Newton once remarked that, in the absence of any other proof, the thumb alone would convince him of the existence of God. The thumb's mobility also comes about because it is on the outside of the hand, unconstrained by fingers on either side and so the tendons and muscles which move it are completely separate.

Human hand joints are covered by a two millimetre thick layer of cartilage which has elastic properties similar to rubber. Cartilage is three-quarters water and the rest is collagen fibres and proteoglycans [4]. The proteoglycans draw in water while the collagen stops the cartilage from swelling too much. The cavity of the joints are filled with synovial fluid, which is also mainly water, but also contains proteins and hyaluronic acid to make it viscous. Synovial fluid is about the same viscosity as lubricating oils and is prevented from draining away by a membrane enclosing each joint. The coefficient of friction of a human finger joint has been experimentally shown to be approximately 0.008, which is as low as that required for good engineering joints.

Good engineering joints have a low coefficient of friction due to different types of lubrication between the surfaces. Hydrodynamic lubrication is a result of a rotating shaft pulling lubricant along with it and gives typical coefficient of friction values of 0.01. Squeeze film lubrication is a result of the shaft taking a short period to sink onto its bearing and friction will still be low if it starts moving within this period. Both hydrodynamic and squeeze film lubrication depend on the viscosity of the lubricant. Boundary lubrication, however, depends upon a single layer of lubricant molecules adhering to the shaft surfaces to reduce friction and gives typical coefficient of friction values of 0.05. It is difficult to understand how human finger joints have such low coefficient of friction values when the joints do not have rotating shafts, and when they have lower coefficient of friction values than boundary friction could account for.

Human joints may have a form of lubrication unknown in engineering. Scientist Charles McCutchen [12] theorised that the water-absorbing nature of cartilage could result in 'weeping' lubrication. This is where the load on the joint is borne by the water in the cartilage rather than the actual cartilage itself owing to the cartilage being made of closed pores. The water does gradually squeeze out but returns if the load is taken off the joint, which is why people shift from foot to foot when standing for long periods of time.

2.2.4 Muscle and Tendon Configuration

The hand has 29 muscles, but some of these have several distinct parts which work separately, with separate tendons connecting them to the bones. Counting these, the effective number of muscles is 38, or almost twice the number of degrees-of-freedom. However, the arrangement of muscles is not simply a pair to work each degree-of-freedom. Most of the hand muscles cross several joints and work them all. Figure 2-3 shows the arrangement of some of the hand muscles and tendons.

Many of the hand muscles are in the forearm and are attached to the hand bones by tendons, which has the effect of reducing bulk. The tendons pass through a narrow channel formed by the carpal bones and fibrous tissue, and spread out so that one superficial and one deep tendon passes into each finger, the superficial being in front of the deep. This means each finger can be bent separately, but connections between the deep flexor tendons make it difficult to bend the little finger without also bending the ring finger. The tendons pass under bands of fibres that hold them close to the joints, so that they do not 'bowstring' out from the bones when the fingers are flexed.

The superficial flexor tendon flexes the middle joint and the deep flexor tendon acts mainly on the last joint of the fingers. The extensor tendon bends both the middle and distal phalanges. The interosseous muscles lie either side of the metacarpal bone and work the metacarpal-phalangeal joint, providing adduction, abduction and bending. This is a total of five muscles to work a four-degrees-of-freedom finger, the absolute minimum needed.

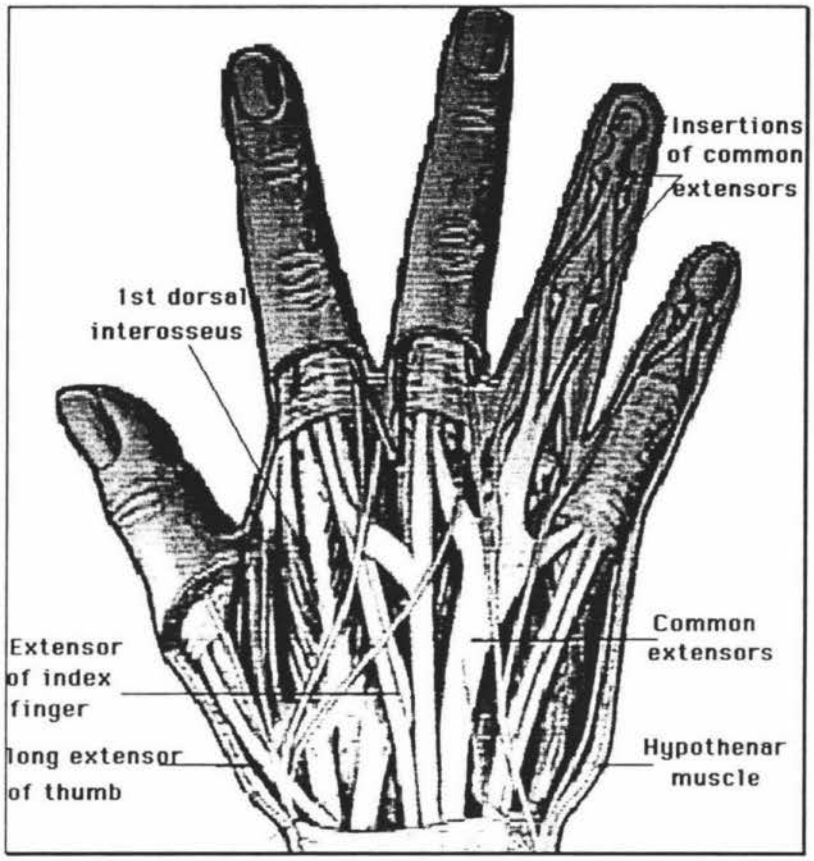

Figure 2-3: Hand muscles and tendons. Adapted from [4].

2.2.5 Nerve Types

The hand is an organ of sense and is amazingly good at manipulation and grasping. These capabilities are possible because of the information provided by the nerves in the hand. Vision also plays a large part in manipulation and grasping, but that will not be considered owing to the desire to use just tactile sensing in PTIRH. Vision is often used when learning to perform a grasp or manipulation, but once learnt vision can become redundant, as in the case of an experienced guitar player who does not need to look at his or her hands while changing chords. Vision also can be used in positioning movements of the arm and wrist to place the fingers near an object, or instead the fingers can feel around, as in a dark room.

Finger positioning and forces applied are measured by nerve endings in the hand muscles, tendons, surrounding tissues, hair follicles and papillary ridges on the palm. Reflex control of the hand is provided by the spinal cord using information from these nerves. Involuntary stretching of the muscles is countered by one reflex, much like a robot has to have a software procedure to counter the effects of sag in joints caused by gravity. More sophisticated control is progressively exercised by higher levels in the nervous system.

There are two types of sensory systems in the human body. The proprioceptive system makes internal measurements which detect the action of the body upon itself. The exterioceptive system includes the nerve endings that detect contact, pressure, texture and temperature, collectively known as tactile sensing [2].

Some of the finger muscles have special nerve endings which provide them with a positional sense that has no equal anywhere else in the body.

2.2.6 Finger Nail Structure

Nails provide a rigid backing and protective sheath for the finger tip. This is of critical importance for the discrimination of textures and the manipulation of small objects. Human nails are composed of keratin, which is derived from the skin. Nails are dead tissue, but are set on living flesh, which has nerve endings.

Nails can be used for many different operations, such as screwing in nails or slitting sellotape. In fact, they are a built-in tool-kit of screwdrivers, tweezers, scrapers, rulers, pliers and cutters.

2.2.7 Configuration of the Skin

The skin is the largest organ of the human body, serving to cover and protect the body, keeping the blood in and the rain out. The skin is very complex, and all attempts to construct an artificial skin which replicates all the functions of natural skin have failed. It is flexible sheath which is waterproof, senses movement and temperature and is self repairing.

The skin of the palm is fat free, except for the ball of the thumb and the heel of the hand, and is firmly bound to the underlying tissue. This enables the palm to make a firm grasp without sliding.

There are three types of lines distinguishable on the skin: flexure lines, tension lines and papillary ridges. Flexure lines are permanent marks produced by the joint movements. The flexure lines therefore reveal how dexterous a hand is. Tension lines provide the skin with the ability to stretch. Papillary ridges are permanent thickenings of the epidermis, the outer layer of the skin. They are found only on the palm of the hand and the sole of the foot. The papillary ridges act as 'micro-switches' to provide a sense of touch. They also contain sweat glands, which help maintain a grip, and somewhat contrarily, the papillary ridges also function like the tread on a car tyre, squeezing away extra moisture. Lubrication also enhances the sense of touch, as the papillary ridges swell.

2.2.8 Summary

The human hand is an amazing construction controlled by the incredible human brain. The structure of the human hand is actually quite primitive, but by use of feedback from the nerves present every two to three millimetres on the skin and in the tendons, it is able to perform an extensive range of movements. Given that the parallel processing power and storage capacity of the human brain will not be able to be imitated for some time yet, this project will have to seek ways to improve on the design of the human hand in order to match its performance.

2.3 Human Hand Grasp and Manipulation Modes

2.3.1 Grasp Modes

Many tasks that are potential candidates for assembly automation involve grasping [5]. Schlesinger [6] considered that the human hand has six generic grasp modes: the pen grasp, used for writing or cutting; the tip grip, often called fingertip prehension; the lateral grasp; the tweezers or scissors grip; the power grasp, sometimes called a palm grip and the pulp pinch. Figure 2-4 shows the generic grasps. The hook grip, where one or more fingers are hooked into a handle or cavity and the spherical grasp, a combination of the tip grip and palm grip where all the fingers and the thumb are evenly spaced around a spherical object, are two more grasps commonly used.

Opposition is perhaps the most important movement of the human hand. Many of the existing robot hands use only a point contact for opposition, but the large contact area between the thumb and finger and the power grasp are important . It is also important to note that the forefinger's bi-axial joint has a small amount of rotation (circumduction).

Without this the fore-finger could not rotate to meet the thumb, which also rotates slightly. The proportion of the thumb to the fore-finger is also important.

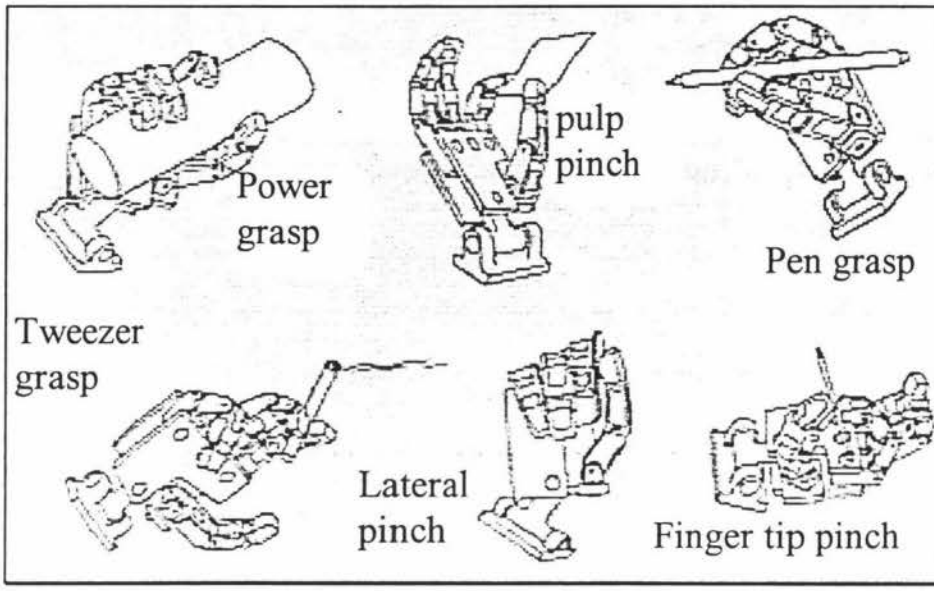

Figure 2-4: The six generic grasps, as defined by Schlesinger. Adapted from [31]

There are two kinds of human hand movements: prehensile and non-prehensile. In a prehensile movement, an object, fixed or free, is held by a gripping or pinching action between the digits or between the palm and digits. Non-prehensile movements of the whole hand include pulling large objects, balancing a tray on the hand or type-writing. Prehensile movements can be further divided into precision and power grasps, which adapt to the objects being held in response to personal preferences and differences in the size and strength of the hand [[7]].

Nine analytical measures can be used to describe a grasp [[8]], as shown in table 2-1.

2.3.2 Manipulation Modes

Manipulation has been defined as a repeated sequence of grasping and regrasping acts [[9]] and as a dynamic grasp [[10]], as opposed to a static grasp where the fingers are locked and the arm is used to move the object grasped. Dynamic grasping has four forms: fixed contacts, rolling contacts, sliding contacts and re-grasping. The planning of these four forms so a robot hand can manipulate an object is a complex problem [[11]]. Most current robot hands are using only finger tip grasps to manipulate objects but some work is being done on whole hand grasp manipulation [[12]]. An analysis of the various manipulations the human hand can perform was conducted [13]. These manipulations originate from the generic grasp modes and may contain a grasp as part of the manipulation. A manipulation was defined as a function of the hand, excluding wrist, elbow and shoulder movements, that requires a movement of the fingers relative to the centre of the hand.

Grasp Analytical Measure	Description
compliance	inverse of stiffness
connectivity	the number of degrees-of-freedom between a grasped object and the hand
force closure	how well the fingers maintain a grip on the object being grasped
form closure	how much the object moves when external forces are applied
grasp isotropy	how well the grasp configuration permits the finger joints to accurately apply forces and moments to the object
internal forces	those forces which can be varied without disturbing the grasp equilibrium
manipulability	how well the fingers impart arbitrary motions to the object
resistance to slipping	the size of the force before the fingers slip
stability	how well the grasp returns to its initial configuration after being perturbed

Table 2-1: Grasp analytical measures.

Thirty functions of the human hand in an office or laboratory were found. These functions include grasps, non-prehensile movements (as in using a push button phone) or manipulations. Some of the functions have variants using the whole arm rather than just the fingers and wrist. For example, a screwdriver grasp is modified if the screw is tight to include all the arm muscles, so as to provide more power.

From these thirty human hand functions nine manipulations were found. These are the trigger grip, flipping a switch, transferring a pipe to grip, using cutters, a pen screw, cigarette roll, pen transfer, typewrite and pen write. It was concluded that only two of these manipulations are necessary for robotic assembly, plus the usual gripping motions. The manipulations deemed necessary were the trigger pull manipulation used for drills and the pipe transfer grip where an object held between thumb and forefinger is transferred into a palm grip. The trigger manipulation also needs a palm grip to be successful. The palm grip would therefore seem to be a very important grasp to ensure that a robot hand can perform.

Typical tasks associated with multi-fingered robot hands include scribing, inserting a peg into a hole, and assembly operations [14]. Common to these tasks is the fact that the robot hand must manipulate an object from one configuration to another, while exerting a set of desired contact forces on the environment.

2.4 Overview of Robot Manipulators

A robot end effector is a very important part of a robot system. The end effector is the bridge between the computer-controlled robot arm and the world around it. In the 1970s and early 1980s grippers were simple two-plate manipulators which only had the ability to open and close and did not provide information about the object they were gripping or their location or orientation.

A move has been made in the last ten years towards more active hands [15]. Active hands have a sense of touch and can re-orientate themselves to a better grip if needed. These properties are taken for granted by humans.

Design of a gripper for assembly operations requires consideration of a number of items. Most important is what is the gripper going to handle. Initially robots were mainly used for pick and place type operations, where the gripper picked up a carefully positioned part and placed it in a predetermined orientation somewhere else.

Later, robots began to be used for assembly and more demands were made on the gripper. It was desired that the gripper should hold the part with some precision and force. As robots were used in assembly more, they began to seem under-utilised only performing one operation. Various strategies were tried, such as having multiple grippers on a single robot arm. This was known as a turret manipulator.

Another strategy tried was to enable the robot to discard a gripper and pick up another [16]. However, these grippers began to become very complex and, more importantly, became a time constraint in the assembly process. Robot engineers began to look at a single gripper that could use many different tools and had a high flexibility. The designs that began to emerge were mainly based on the human hand.

2.5 State of the Art in Robot Hands

2.5.1 Prosthetic Hands

The research into artificial hands began with prosthetic hands. In the sixteenth century a German knight had a mechanical hand made to replace that which he lost in combat [17] and there are other instances where hooks were used to replace a hand. Many other artificial hands have been made to replace hands lost in combat or through accident. Prosthetic hands are often designed for form rather than function but sometimes include manipulating ability as well as a basic pinch.

There are many prosthetic hand designs, most of which have only a limited range of grasps and can not manipulate objects. An example of a prosthetic hand is the WIME Hand [18] which is of the crossed four bar type that curls the finger joints towards the palm. A Russian design is similar, except the thumb can also move. A Swedish design uses tendon cords to drive each finger [19]. A more advanced Japanese design is reputed to be able to twirl a baton [20]. The University of Utah began its investigations into dexterous hands with sophisticated myoelectrically controlled prosthetic hands and work is still continuing in this area, with particular application to telerobotic applications in space [21].

2.5.2 Dexterous Robot Hands

2.5.2.1 Belgrade/USC Hand

Development began on the Belgrade/USC hand in the late 1960s. The Belgrade/USC hand is a spring-restrained tree mechanism that adapts itself to pick up different objects [22]. It has four fingers and one thumb, each of four degrees-of-freedom. Four motors provide the power for the hand, two for the thumb and two for the fingers. The hand has a payload of 2.2 kilograms. Closing the fingers takes two seconds from full extension and the thumb one second. The full set of Schelisinger's grasps are possible [23]. Finger position information is provided by absolute position linear potentiometers with force information provided by twelve logarithmic force sensors.

2.5.2.2 Hitachi Hand

The Hitachi hand [24] has three fingers and a thumb, each of four degrees-of-freedom. Shape memory alloy (SMA) techniques power the hand. The hand and drive assembly weigh a total of 4.5 kilograms. The hand has a payload of two kilograms. Each finger has 12 SMA actuators. When the 0.02 millimetre in diameter wires of nickel and titanium alloy are heated by electric current the metal contracts against the force of a spring. Modulating the current varies the joint angle. This technique has advantages, such as a reduction in weight and a decrease in complexity. A joint speed of 90 degrees per second of joint travel is possible. Finger position information is provided by potentiometers on each actuator.

2.5.2.3 Odetics Hand

The Odetics hand [25] has been described as having two thumbs and one finger, with the 'thumbs' having three axes of movement compared to the two axes of movement of the finger. The kinematics of the hand are very simple, so it has low dexterity but is capable of a wide range of grasps. An interesting mechanical design feature is a dual speed mode, where a force sensor detects contact with an object and slows the motors.

2.5.2.4 Omni-Hand

The Omni-Hand [26] won the 1993 NASA Technology Utilisation Award, was built by Ross-Hime Designs and was funded by NASA. The hand has two fingers and one thumb, each of four degrees-of-freedom. Direct drive electric linear actuators power the hand. The proximal knuckles have poly-axial joints, identical to the human hand. Each finger has six kilograms of vertical lift. Each actuator contains an encoder for position information and tactile sensors are used on the fingertips.

2.5.2.5 National Taiwan University Hand

The NTU Hand [27] has four fingers and one thumb. The thumb and index finger are each of four degrees-of-freedom, and the other three fingers are each of three degrees-of-freedom. High performance DC micro motors power a set of gear trains to rotate the joints. The hand weighs a total of 1.6 kilograms, is human sized and is nearly completely self contained, including the control system. The only external connections required are for power and a RS232 connection to a SUN workstation for high level computation. A hierarchical fuzzy control system is used. Maximum output joint torque is 3661.9 g-cm. Objects up to one kilogram can be grasped and objects up to 0.5 kilograms can be manipulated. Potentiometers sense the joint position via a connection to the gear train and the hand has eighteen tactile sensors. In addition to dexterous manipulation a power grasp is possible. The hand is intended for prosthetic and industrial use.

2.5.2.6 Stanford/JPL Hand

The Stanford/JPL hand [28, 29], often known as the Salisbury hand, has two fingers and one thumb, each of three degrees-of-freedom. DC servo motors provide the power for the hand and it is actuated by artificial, teflon coated, tendons. Each finger has four push-pull tendons. The hand and drive assembly weigh a total of 6.6 kilograms. Output force is a maximum of 4.5 kilograms for a maximum of two minutes. The hand is capable of manipulations and grasps for objects three centimetres in diameter. For objects of this size the hand configuration was optimal and could maintain a stable grasp while imparting arbitrary motions to the object [30]. The hand uses only fingertip prehension to pick up objects. Finger position information is provided by motor position sensors with force information provided by strain gauge sensing of the tendons.

The artificial tendons have large hysteresis, with ten Newtons of force at the motor end being reduced to six Newtons at the fingertip. The proximal knuckle on the human hand is imitated by two joints which do not have intersecting axes. This causes problems with dexterity, but is simpler than imitating the human knuckle.

2.5.2.7 Utah/MIT Hand Projects

Research into universal grippers has been carried out in a joint project between the Artificial Intelligence Laboratory at the Massachusetts Institute of Technology and the Biomedical Group at the University of Utah.

2.5.2.7.1 Utah/MIT Dextrous Hand (UMDH)

The UMDH [31, 32, 33, 34] has three fingers and one thumb, each of four degrees-of-freedom. Pneumatic double acting glass cylinders provide the power for the hand and each joint is actuated by a pair of antagonistic tendons. The force exerted at the fingertips is 3.18 kilograms and the hand is capable of movements at 20 Hertz. The proximal knuckle is a roll/pitch design, which doesn't quite imitate the human ball and socket, with no circumduction. Hall effect sensors provide joint angle information and are also used to monitor tendon tension. The hand can roll tin cans, screw in light bulbs and perform many other grasps and manipulations.

The artificial tendons have caused many problems in the final design, with a large problem being unpredictable failure due to wear at transition points. A system of 288 pulleys is needed to reduce friction and control is difficult due to the compliant nature and length of the tendons.

2.5.2.7.2 Sarcos Hand

The Sarcos hand [35] was also developed by the Utah/MIT group and uses many of the techniques developed for the UMDH. It is a simplified hand without the multitude of tendons and pulleys the UMDH has. The Sarcos hand has one thumb and two fingers, one of which is fixed in position. The hand is hydraulically actuated and consequently has a load capacity of 22.7 kilograms. The fixed middle finger provides a stable reference point for the Hall effect sensor used to find the position of the other two digits. The Sarcos hand has a range of grasps.

2.5.3 Comparison of Robot Hands

In order to ascertain which design features from the state of the art robot hands to include in PTIRH, a comparison was made, which is shown in table 2-2.

	No. of fingers & thumbs	No. of degrees of freedom	Actuation type	Weight	Payload	Sensors
Belgrade hand	4 fingers, 1 thumb	20	Geared DC motors	-	2.2 kg	potentio-meters & force sensors
Hitachi hand	3 fingers, 1 thumb	16	SMA	4.5 kg	2 kg	potentio-meters
Odetics hand	1 'finger', 2 'thumbs'	8	DC Motors	-	-	force
Omni-Hand	2 fingers, 1 thumb	12	Direct drive electric	-	12 kg	encoders and tactile
NTU Hand	4 fingers, 1 thumb	17	DC micro motors	1.6 kg	1 kg	potentio-meters & tactile
Salisbury hand	2 fingers, 1 thumb	9	DC servo motors & tendons	6.6 kg	4.5 kg for a max. of 2 minutes	motor position & strain gauges
UMDH	3 fingers, 1 thumb	16	pneumatic & tendons	-	3.18 kg	Hall effect
Sarcos hand	2 fingers, 1 thumb	6	hydraulic	-	22.7 kg	Hall effect

Table 2-2: Comparison of robot hands.

2.6 Conclusion

The physiology of the human hand is in some ways complex, and in some ways, simple. The bone structure is a primitive design, but the hand is capable of so much with the sensitivity imparted by the nerves of the hand, the dexterity provided by redundant degrees-of-freedom and the intelligent control provided by that marvellous parallel processor the brain. The human hand provides proof that the anthropomorphic configuration, properly controlled, is successful and gives a target to aim at for robot hand researchers.

The simple two 'fingered' gripper is still in use in many applications, probably because it is so simple. However, simple grippers are proving to become a constraint in some applications. Robotics engineers are searching for a universal gripper, which will aid robots to achieve their full potential.

Many people are experimenting with anthropomorphic hands with varying results. Successful examples of anthropomorphic hands are mainly using a tendon-based design. This design has problems in that it is very complex and prone to catastrophic tendon failure.

The research into robot hands has been under way for at least thirty years, with varying success, but robot hands have not yet made their debut into the factory or appeared on a home service robot. This would seem to imply that the concept of the robot hand is lacking in some area.

In Chapter Three, the design process for a robot hand with potential to overcome the problems with current robot hands is outlined.

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Chapter 3

DESIGN PROCESS AND IMPLEMENTATION OF DESIGN

3.1 Introduction

The design process was cyclical in nature, with the design problem considered, leading to draft designs and the implementation of the design. The implementation of the design could show problems in the design and hence the design would change, and these changes would then be implemented. Each time around the cycle, knowledge is gained about the potential of the concept and modifications are made.

The design process outlined in this chapter presents in a logical order the design problems encountered and how they were solved. Chapter Four discusses the evaluation of the design and PTIRH concept. Evaluation was constantly undertaken, sometimes in a very ad hoc manner, as is often the case in engineering situations. These evaluations would often lead to a design change.

Section two considers the desired design goals. Sections three and four discuss actuators and sensors respectively. Section five gives mechanical design. Section six outlines the construction of the finger and its implementation and section seven concludes this chapter. The analysis of the prototype is presented in Chapter Six.

3.2 Design Goals

3.2.1 Introduction

An anthropomorphic based robot arm, such as the ASEA five degrees-of-freedom robot in the Department of Production Technology, has three joints. There are the shoulder (the base) and wrist joints which can rotate and bend and the elbow joint which can only bend. The ASEA robot is connected to a large control cabinet with a control panel, disc drive, joystick and hardware for processing, input, output and communications. The software is a simple form of functional programming (similar to BASIC), using point-to-point positioning once the end effector has been 'jogged' by the joystick to the appropriate position. The robot arm can also be programmed off line by using ABB CommTools. The joints use DC motors, resolvers provide feedback on the joint positions and tachometers provide velocity information. See figure 3-1 for a picture of the robot arm.

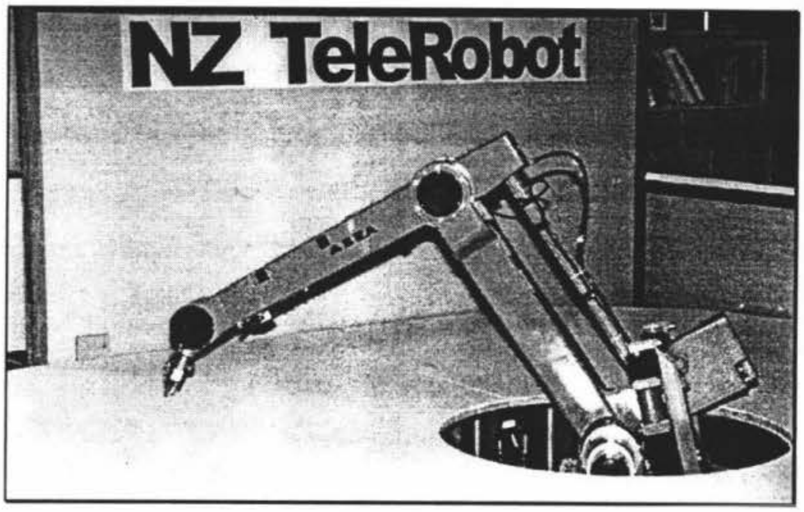

Figure 3-1: The ASEA robot arm.

As described in section 2.5, state of the art robot hands are composed of up to five digits. In some of the hands, each digit has a joint with two axes (pitch and yaw) and two degrees-of-freedom and two joints which have one axis (pitch) and one degree-of-freedom. The hands often have a wrist which can pitch, yaw and roll, giving a total for the hand of 3 axes and 23 degrees-of-freedom. Each digit has an actuation system, sensors, power and a control system. Each digit is often approximately human size and, in effect, is a very small robot. The hand as a whole must have a control system which coordinates the movements of the digits in a cooperative manner.

When considering the design goals for Production Technology's Intelligent Robot Hand, it is important to bear in mind that a robot hand is composed of small robots which are designed to work together and therefore the robot hand has a complex control system.

3.2.2 Performance Tasks for PTIRH

At one end of the scale PTIRH will be used for small assembly operations, which comprise 75 percent of assembly operations performed by robot grippers [[1]] and at the other it is desired it should be able to grasp and manipulate large objects.

3.2.3 Hand Configuration

For the majority of robotic assembly tasks two 'fingers' are sufficient. However, three fingers are needed to perform dexterous tasks in an unstructured environment [[2]] and for a grasp to achieve force closure of a two-dimensional object [[3]]. For force closure of three-dimensional objects and for some tasks of a manipulative nature more digits are required. More digits mean that there is kinematic and actuation redundancy in the design [4] so the hand will be able to perform the same manipulation in different ways and adjust the gripping forces [5]. Extra digits also mean that the grasps chosen need not rely on friction to be stable.

It was concluded that at least four fingers are needed to provide enough digits for successful grasping and manipulation. It was decided to design and partially build a hand with two thumbs, as robot hands with one thumb have not yet made the step out of the research laboratory into the factory or home. Wright and Bourne [6] believed a hand based upon the Utah/MIT hand would enter industrial use by 1999, but recent literature does not support this ten year old prediction. By building a hand with two thumbs research can then be conducted to validate the claim that a robot hand with two thumbs will perform better in an industrial work place than a robot hand with only one thumb. Two thumbs will also be a novel design challenge.

The hand will have two fingers to increase the total number of digits to the minimum number necessary to manipulate three-dimensional objects and will also give two pairs of opposable digits capable of independent gripping. This will give rise to economy of movement as in the following situation: the first thumb/finger pair could grasp a rough part using a simple pinch and carry it to a finishing station. The second thumb/finger pair could pick up a finished part, load the rough part with the first thumb/finger pair and return with the finished part. Having two thumbs and two fingers is a symmetrical configuration so will also allow the hand to be ambidextrous.

Therefore, initially PTIRH will be non-anthropomorphic and will have a configuration of two fingers and two thumbs. Figure 3-2 shows an early conceptual view of PTIRH. The author believes this configuration in an industrial robot possesses advantages over the one thumb of a human hand and current robot hands. An exhaustive search of the available literature on state of the art robot hands has not revealed any of this configuration so novelty is also a factor. More fingers will be able to be added later should experimentation and analysis of the initial configuration show that they are necessary.

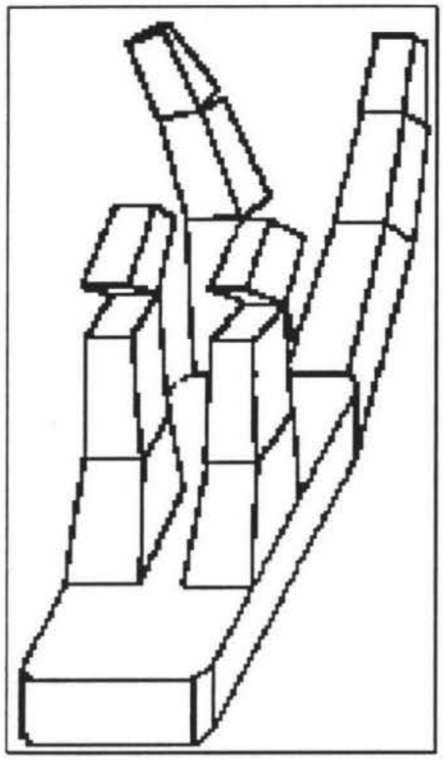

Figure 3-2: Block view of PTIRH showing the two thumbs, two fingers concept.

3.2.4 Weight Considerations

Initially, the gross positioning of PTIRH will be performed manually and by an ASEA robot that has a wrist axis. The hand will need to stay within the six kilogram payload limit of the robot and the hand itself will ideally have at least a one kilogram payload. PTIRH is intended to be used in light assembly operations and so the small payload is not a limiting feature. A final year project in the Production Technology Department in 1995 was the design and development of a three degree-of-freedom robot wrist [[7]], which was never completely implemented due to time constraints in the project. This wrist weighed 1.2 kilograms and so the maximum weight constraint for PTIRH is 3.8 kilograms. Compared to other hands this is a low hand weight, although other hands include the drive mechanism in the total weight and this is often located on the forearm of the robot. It could be possible to locate some of the drive mechanism for PTIRH on the robot forearm also, in order to reduce the weight of the actual hand. Table 2-1 shows the weights of other robot hands.

3.2.5 Number of Axes and Degrees-of-Freedom

It is intended that each of PTIRH's four digits be based on the design of the human digits. This means each digit will have two axes of movement with four degrees-of-freedom. The two extra degrees-of-freedom are not strictly needed but allow the finger to have redundancy and hence avoid having singularities in the work envelope. The vertical axis will have three joints, each capable of a ninety degree range of movement. The horizontal axis will have one joint capable of a 30 degree range of movement. It is desirable that the proximal joint has circumduction so that it will be able to have full opposition. The joints are all revolute joints, mimicking the synovial hinge joints of the human hand. The thumb will have pitch and roll instead of the pitch and yaw the fingers have. Figure 3-3 shows a diagram of the finger, with each degree-of-freedom and axis noted.

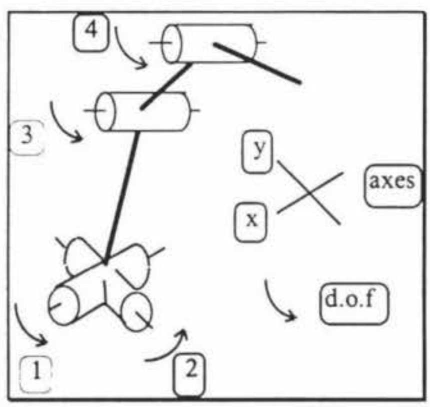

Figure 3-3: The structure of each of PTIRH's fingers.

3.2.6 Desire for Modularity

Because of a desire for modularity in the digits, the number of fingers can be easily increased if experimentation and analysis shows this to be necessary. The proximal joint of the thumb will be different from that of the fingers but the digit itself will be modular. Modularity will allow for ease of construction and repair. Modularity will allow for the same parts to be used in the hand and so the cost will decrease. Maintenance will be easier, as a damaged finger will be able to be entirely replaced, hopefully eliminating time consuming calibration of the whole system.

3.2.7 Hand 'Intelligence' Considerations

PTIRH is to be an intelligent robot hand that will be able to perform many different functions, be more universal than the standard two jaw gripper, and is a step along the journey towards a universal end effector. Research on Intelligent robotics is progressing worldwide [8, 9, 10, 11, 12, 13, 14]. Intelligent robotics was defined in section 1.1.

The sensing abilities of PTIRH determine the level of its intelligence. Sensors provide the feedback path to enable decisions made by the PTIRH controller to be made with reference to the environment in which PTIRH is operating. The information gained from the sensors will need to be processed in some form in order to gain useful information. Research is being carried out in the area of intelligent sensors [15, 16] where the signal processing of a sensor's data is carried out before being sent to the controller. Intelligent sensors would reduce the work the PTIRH controller would need to do, so will be an area to examine.

The sensors should be mechanically and electrically robust and of good accuracy. The number of sensors should ultimately be kept to a practical minimum and should have a lengthy operational life.

Another issue with PTIRH's sensors is redundancy. In the interests of robustness, redundant sensors are necessary. The problem then is that three redundant sensors are needed in order to gain a majority decision on the information provided. Detection of faulty sensors then becomes important. Fusing of the information gained from redundant sensors is another large area of work [17]. Redundant finger sensors will also enable PTIRH to position fingers more appropriately in order to gain better sensor readings.

The sensors will not include a vision system as tactile sensors can provide information that vision systems can only infer [18, 19, 20, 21]. Real time processing of tactile sensor information will be quicker than visual sensor processing as less data will need to be analysed. Vision systems require that the object being sensed is known *a priori* [11]. Once the known object is located, and recognised, its orientation has to be provided so that a gripper can manipulate it. Vision sensors can not provide information about gripping forces. There is, however, potential for a vision system to be added should experimentation and analysis show it to be necessary.

PTIRH will initially have many different types of sensors while experimentation is carried out to determine how many and what sort of sensors are optimal. The number of sensors should be at a minimum in order to carry out tasks effectively and efficiently. Ideally, an element of synergy will be achieved from having multiple sensors.

3.2.8 Size Considerations

The size of PTIRH will be as close as possible to the size of a large human hand. This is because it is believed by the author that there are no problems caused by size in a large human hand and it is wished to reduce the effects of inertia to a minimum. Any size constraints will be imposed by the actuator that is used for the hand.

The aim is to build a hand that can perform much the same sort of tasks that a human can perform and so it would be preferable that PTIRH could use human tools. However, to initially prove the concept of PTIRH, size will not be important as applications will be found, whatever PTIRH's size.

3.2.9 Form Considerations

PTIRH is intended to be used as a multi-finger manipulator for automated assembly and parts handling operations. The form of the hand is a secondary consideration to the function the hand would perform, and this will bar the hand from use in prosthetics. It is intended that applications will be found in the factory, the home, or space exploration.

3.2.10 Performance Objectives

PTIRH should be as fast moving as a human hand, have a high reliability of operation and be able to position held objects with a high degree of accuracy and precision. The hand should have similar static, dynamic and kinematic characteristics to the human hand. Dexterity of the hand is more important than power considerations. The sensitivity of PTIRH will be related to the control system and the number of sensors, but should be approaching the sensitivity of the human hand. The work envelope of PTIRH should be as good as a human hand, allowing for having one less digit.

3.2.11 Compliance Considerations.

Compliance allows a finger to press against an object and follow its contours. An effective robot hand will need to have a large degree of compliance [22, 23, 24, 25, 26].

Controllable active compliance necessitates both positional and torque information about a joint. Passive compliance is also a possibility, but this is essentially deformability or conformability of a joint to a particular position and it would be desirable to be able to actively control the compliance in a joint. This would allow better precision and knowledge of the precise position of an object being grasped or manipulated.

3.2.12 Cost considerations

Cost of PTIRH is important for two reasons. Firstly, it is hoped that the final, fully developed, form of PTIRH would be able to be sold for use in industry, space or the home. Therefore the price of the components should be as low as possible to enable a suitable mark up to cover the research and development. Secondly, this project is being run on a small budget so expensive solutions to problems are not an option. It is intended that any components be easily available off the shelf.

3.2.13 Summary of Design Goals

To sum up the goals for PTIRH, a design is wanted which will achieve the following:

- manipulation and assembly
- two fingers and two thumbs, each of four degrees-of-freedom
- weigh less than 2.8 kilograms and be of modular design
- be intelligent and be a test bed for many different types of sensors
- be as close to human hand size as possible, but suitable applications will be able to be found if this is not the case
- be similar in performance to the human hand.
- be actively compliant
- be of low cost.

3.3 Choice of Actuation

3.3.1 Introduction

The design goals given in section 3.2 are first applied to the type of actuation to be used for PTIRH. The type of actuation will have a large impact on the ability to achieve the performance tasks, the weight, the size, the cost, the performance objectives and the active compliance of the hand. These hand design goals give rise to goals for the actuators of the hand.

3.3.2 Actuator Selection Goals

The selection goals for the actuators are derived from the design goals of PTIRH.

The actuators should be:

- of low weight
- fast acting
- of low cost
- of high power
- preferably of small size
- of a type to allow active compliance.

All bar the last goal are even more important when consideration is made of how many actuators are to be needed for four digits each of four degrees-of-freedom.

3.3.3 Overview of Robot Hand Actuators

Actuators are the energy conversion devices in robotics. In robot hands, energy (usually electrical energy) is converted into movement of the hand. The three main robot actuators are:

- electrical motors which turn electricity into (usually) rotary motion
- hydraulic systems which use an electrical pump to produce both rotary and linear motion
- pneumatics which use electric compressors to produce linear or rotary motion

Table 3-1 gives a summary of the advantages and disadvantages of the three main types of actuators.

Actuator	Advantages	Disadvantages
Pneumatics	• low cost • high speed • simple "bang-bang" control possible • high power/weight ratio compared to electric actuators • direct drive possible • inherent compliance	• position control difficult • need for control valves and air supply • air compressibility a possible disadvantage • noisy
Hydraulics	• high power/weight ratio • low backlash • direct drive possible	• constant maintenance needed to avoid hydraulic fluid leaks • expensive • servo control complex
Electrics	• accurate position and velocity control • relatively cheap • compact power supply possible • inherent self braking with high ratio gear boxes	• low power and torque/weight ratios • possible sparking • problems with direct drive • high rpms necessary for maximum efficiency • prone to overheating when high torque required • backlash a problem with gearing

Table 3-1: Comparison of the three main types of actuation.

Other experimental actuators include: shape memory alloys [27], magnetostrictive materials [28], polymeric artificial muscles [29], piezoelectric [30] and electro-rheological fluids [31]. Most of these have a basis of hydraulic and electrical techniques.

Pneumatic techniques have been explored such as the Goodrich Elastro-actuator and more recently the Shadow Robot Project air muscle [32], Utah/MIT hand double-acting pneumatic actuator [4], a hybrid electro-pneumatic actuator known as the 'Penram' [33], the McKibben pneumatic artificial muscle [34] and the University of Salford braided pneumatic muscle actuator [35]. Pneumatic actuators' small size, power to weight ratio, inherent compliance and ease of use are factors which could have great success in the robot hand area.

3.3.4 Choice of an Actuator to Meet the Specifications

A fundamental consideration when choosing an actuator for application in a robot hand is whether to use a direct or remote drive actuator. A remote drive actuator, such as in the Salisbury hand and the Utah/MIT hand, is located on the forearm of the robot arm to which the hand is attached. This is done in order to reduce the weight of the actual robot hand and to allow space for internal instrumentation and structures of the robot hand. The robot hand is therefore operated by artificial tendons, antagonistically in the case of UMDH. The tendons introduced problems in the design of the UMDH, such as the addition of 288 pulleys to reduce friction and the manufacture of complex artificial tendons to reduce stress breakages. A second problem with tendons is also associated with friction and stress: the force applied by the actuator will be reduced by the passage around pulleys and stretching of the tendons. Control of tendon operated systems can therefore become problematic.

A direct drive actuator is located at the joint itself, thus eliminating the need for tendons and associated problems. However, direct drive actuators have their own problems, with weight being the first and most obvious. A direct drive actuator at each joint could make the robot hand too heavy for the robot arm to which it is attached. An associated problem is size, with direct drive actuators taking up space needed for sensors. However, it is the authors view, and the view of other researchers [[36], [37]] that direct drive actuation should be used in preference to remote drive owing to the disadvantages of current remote drive systems.

<u>3.3.4.1 Electric actuation</u>

Electric actuation was considered first as this form of actuation has many advantages over hydraulic and pneumatic actuation. Ease of control and the simplicity of electric power were attractive considerations.

Direct drive electric motors are available, which don't use any gearing to drive the joint, but these are often expensive. Advances in direct drive electric motors are occurring rapidly and will certainly offer advantages when the price of such actuators drops. Another possibility would be to use a small, high performance motor and use gearing. Weight considerations then begin to become important as does cost and gear backlash. Gearing is an added complexity that would be avoided by preference.

3.3.4.2 Hydraulic actuation

Hydraulics were discarded as not being suitable for the small size of the robot hand. The high cost, control problems and complexity were also issues that weighed against the implementation of hydraulic actuators in PTIRH.

3.3.4.3 Pneumatic actuation

Conventional pneumatic rams were disregarded as being impractical due to the weight and cost of small cylinders. However, the inherent compliance, power-to-weight ratio and potential for direct drive were points in favour of pneumatic actuation.

A search for more unusual pneumatic actuators discovered the Shadow Robot Project's air muscles. The air muscles looked promising so a sample of the muscles was ordered for experimentation.

These air muscles had a high power to weight ratio of 400:1, were lightweight and low cost. They were inherently compliant due to the compressibility of air and when operating antagonistically could have the compliance controlled actively. The manufacturers stated they were similar in size to human hand finger muscles so therefore should prove suitable for a human-hand-sized robot hand. The air muscles could be quickly filled with air to produce fast acting movement and were a direct drive actuator.

The air muscles thus fulfilled all of the actuator selection goals given in section 3.3.2 and were selected as the actuator of choice for PTIRH. The next section describes the air muscles and outlines their method of operation.

3.3.5 Description of the Air Muscles

The air muscle is made by an organisation known as the Shadow Project Group, based in London, England. The air muscle is supposed to mimic the behaviour of an organic muscle and can be used in place of a high pressure pneumatic ram at a fraction of the cost. The manufacturers claim that the air muscle has no stiction, is easily controllable and is exceptionally powerful.

The air muscle consists of a rubber tube covered in a tough netting made of braided plastic. When the muscle is stretched and the rubber tube inflated, the air muscle contracts as the rubber tube expands against the plastic braiding. The braiding acts like a pantograph so as it expands the muscle gets shorter. Metal crimps are used to hold the ends of the braid to stop the air escaping and so a loop is formed for an attachment point.

The mini air muscle which is going to be used as the actuator for PTIRH weighs a mere five grams. It can get wet, be filled with liquid, operate under water and works bent round a curved object.

The air muscle is an ideal actuator for reciprocal movements, such as the movements the human hand makes. The muscles contract about 25 percent of their length, if they are at full stretch to start with.

3.4 Choice of Sensors

3.4.1 Introduction

The design goals given in section 3.2 are next applied to the type of sensors to be used for PTIRH. The type of sensors will have a large impact on the achievability of the performance tasks, the intelligence, the cost, the performance objectives and the active compliance of the robot hand. These robot hand design goals give rise to sensor selection goals for the sensors for the robot hand.

3.4.2 Sensor Selection Goals

As is to be expected the sensor selection goals are derived from design goals of PTIRH, with some specific to sensors.

The sensors should:

- be mechanically and electrically robust
- be accurate and precise

- have a lengthy operational life
- be of low cost
- be of low weight (although not a large consideration, as sensors are usually light weight)
- use as few wires as possible
- have a large output range
- be easy to calibrate
- not need initialisation or a warm up period

3.4.3 Overview of Robot Hand Sensors

Robot hand sensors can be divided into two basic types: internal state sensors, which measure the position, velocity or acceleration of the joints, and external state sensors, which measure the robot hand's geometric and/or dynamic relation to its environment or the object that it is handling. The latter type can be visual or non visual sensors. As discussed in section 3.2.7, visual sensors will not be used. For PTIRH the initial step of finding the object will be performed by placing the object into a limited space, which PTIRH will then explore using its tactile sensors. Tactile sensors provide information about the object that is being grasped. Another non-visual sensor is the force sensor, which provides information about how hard the object is being grasped.

To imitate the sensing abilities of the human hand, the tactile elements of PTIRH should be able to detect tangential and shear forces (to detect if the grasped object is slipping), resilience of the object, texture and shape. Sensors have been developed in response to these requirements but to date there is no one sensor to detect every requirement. Most tactile sensors can only detect one or perhaps two of the variables.

Slip sensors have to date used two techniques: small rollers which rotate with slip and use of a probe which contacts the object surface. Another technique is the lift and try approach. If the grasp is not tight enough and the object slips out when lifted, then try again with a tighter grip.

Texture sensing is an area where little research has been done. The human finger finds it very easy to discriminate between surface texture when rubbed over the object but this is not easy to replicate. However, work has been done on allowing a texture sensor to come into contact with one area of an object and register the texture in that specific area.

There are many different types of force sensors. These include capacitive, magnetoresistive, piezoelectric, resistive and optical techniques.

Joint position sensors include potentiometers, resolvers, LVDT techniques, optical interrupters and optical encoders. Velocity sensing can be done using the position sensor's information with respect to time.

Proximity sensors are useful to have on a robot hand. They can provide information about how close the robot hand is to an object and in which direction there is an object. Proximity sensors types include reflected light, scanning laser, ultrasonics, radar, eddy current, resistive, Hall effect, air pressure and capacitive.

As the air muscles are to be the actuators for the robot hand, an air pressure sensor will be needed. This could use many of the techniques of the force sensors.

Initially PTIRH will have three types of sensor: air pressure, force and position. Later sensors such as tactile arrays, surface roughness, slip, proximity and temperature may be added.

3.4.3.1 Pressure Sensors

A pressure sensor is provided on the air muscles to give feedback to the robot hand controller. This gives a direct value to the controller to use to compare with desired pressure readings, which will be a function of the desired position and force values.

Two pressure sensors were constructed by Mechatronics Technician, Ken Mercer. The first was a strain gauge based sensor, where the change in strain on a diaphragm represents a change in pressure. Signal processing is needed to amplify the signal from the strain gauge before the analogue-to-digital conversion.

The second sensor is a capacitive sensor, where the change in pressure produces a change in capacitance of the sensor which can be directly converted to an analogue voltage output without amplification.

Both sensors are a reasonable match to the sensor selection goals given in section 3.4.2. An evaluation of the sensors is presented in section 4.3.

3.4.3.2 Joint Position Sensors

Simple, low cost and small potentiometers have been installed to give PTIRH information regarding the angle of the joints. The only signal processing needed is a simple analogue-to-digital process, which can be handled by the microcontroller presently being used for low level control. Potentiometers do have problems in the area of mechanical robustness, wear and calibration, but it remains to be seen how much of a problem.

3.4.3.3 Force Sensors

PTIRH has one Interlink force sensor to be installed in the fingertip. This sensor is known as a FSR (force sensing resistor) and returns an analog voltage dependent on how hard the fingertip is pressing against an object. Designed as a "smart" sensor, the FSR can distinguish between objects of various profiles and weights. They are rugged and are ideally suited to working in harsh environments with rubber or metal overlays. Durably constructed the FSR can perform millions of repeated operations [38] and is insensitive to vibration, electrostatic discharge, electromagnetic interference, grime and solvents. The FSR has a thin profile and is available in custom configurations. Arrays of the FSR are capable of conveying both object position and force information More force sensors will be installed on the inside of the finger and palm surface to provide results for grasps involving the whole hand. This sensor also fits the sensor selection goals. Figure 3-4 shows the FSR located on the fingertip of PTIRH.

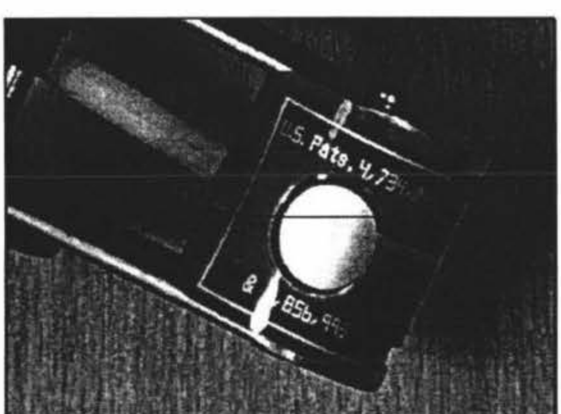

Figure 3-4: Force Sensing Resistor for force and tactile sensing

3.5 Mechanical Design

3.5.1 Introduction

The mechanical design of PTIRH attempts to achieve the design goals given in section 3.2. These design goals have already been used to develop specifications for the actuators and sensors for PTIRH. From these specifications an actuator (the Shadow Robot Project air muscle) and sensors (position, force and pressure) have been chosen. This section on the design process is about the implementation of a robot hand design using the air muscle.

The hand design can be broken down into four sections. Firstly there is the design of a valve to control the pressure of the air in the air muscles, thus enabling them to have position control. Secondly there is the design of a modular finger for PTIRH. As the air muscles have not been used in this application before it is unknown how it will perform so only one finger will initially be built as a prototype and tested. Thirdly, there is the design of a thumb joint and fourthly, the design of a palm on which to base the fingers.

Section 3.5.2 discusses the design of a valve to control the air muscles. Section 3.5.3 then covers the design of a finger joint using the air muscles as actuation. Section 3.5.4 shows the design of the universal joint at the base of the finger. Section 3.5.5 is the design of the fingernail and section 3.5.6 is the design of the fingertip. Section 3.5.7 combines the design of the previous two sections to produce the design of the whole finger. Section 3.5.8 outlines the design of a palm on which to base the finger design.

3.5.2 Design Of A Servo Pneumatic Valve

3.5.2.1 Introduction

A disadvantage with the air muscles is similar to that of all pneumatic actuators: they need a pneumatic control valve. In particular, the air muscles need to be supplied with compressed air at different pressures in order to bend the joints of PTIRH to intermediate positions. A resolution of at least one degree of movement for each joint was required and the speed of response had to be as quick as possible.

3.5.2.2 Background

A search was carried out for means suitable for the purpose of controlling the air pressure of the air muscles. A simple solenoid valve would only allow either to fill completely, or deflate completely, the muscle. Other researchers using air muscles were using manually adjusted regulators linked to a reservoir with a solenoid valve [34], single stage flapper valves actuated by voice-coils [[39]] or electrically driven, low-power piezoelectric valves [35]. An approach was desired which removed the human operator and was not too large in size. The manufacturer of the muscles was selling air muscle kits to schools with simple solenoid valves and was very reluctant to release any information regarding how they are themselves controlling the air muscles for their Shadow Robot project

Two different types of valves emerged as the contenders for controlling the air muscles. First, there was the 'leaky' valve. With this valve there was a constant outflow of air from the muscle and the pressure was varied by pulsing an inlet valve. There were concerns over issues such as the efficiency, speed of response and control aspects of such a valve. The second type of valve considered was the servo pneumatic type. This is two valves in series, an inlet and an outlet, controlling the differential pressure of an port located between them. The differential pressure is raised by switching on the inlet valve and lowered by switching on the outlet valve. Only one valve was to be on at any one time. A pressure sensor was to be used as feedback.

The latter type of valve was considered to be the best for the air muscles application due to the possible speed of response and simplicity of such a design.

Servo pneumatic valves are readily available off the shelf. They were expensive at around $1000, and had slow response times of 25 milliseconds to switch on. It was decided to investigate the design and construction of a low cost servo pneumatic valve to use with the air muscles.

3.5.2.3 Design considerations

The essential building block of the servo pneumatic valve is two fast acting solenoid valves. A research project in the Department of Production Technology had resulted in a valve for the application of automatic fly spraying [[40]]. This valve was lightweight, inexpensive and fast operating. There were several valves which were surplus to requirements which could be used to conduct testing. The initial design step simply took the form of finding the appropriate connectors to transform the two single-acting valves into one unit. Tests showed the concept would work and would have a response time of 20 milliseconds, less than that available in commercially produced valves.

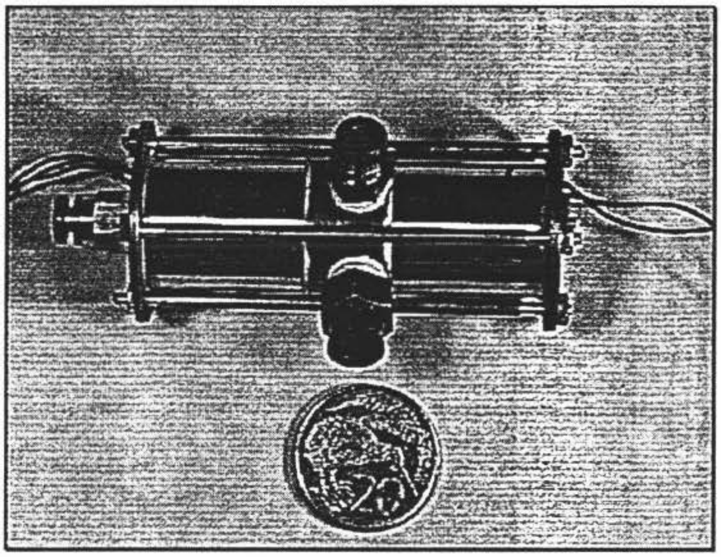

Figure 3-5: The servo pneumatic valve.

The fly spray valves had some problems with leaking connectors due to the fact that they were not designed to be used in such an application. The coil connector wires were also delicate and broke easily. It was considered that switching times of the valve could be further reduced by designing and building two solenoid valves as a single unit to function as a servo pneumatic valve. The robustness and ease of connection of the entire servo pneumatic valve could then also be improved. Extra coil windings were added and the entire valve was made out of steel, instead of injection moulded plastic with metal inserts. Figure 3-5 shows the complete valve unit.

3.5.3 The Design of a Phalangeal Joint Using the Air Muscles as Actuation

The air muscle is often used with a simple lever consisting of two links and a simple pivot joint, as shown in figure 3-6. This is a revolute type of joint which is very common in robots. A joint range of movement of ninety degrees was desired, similar to the human finger joint. The range of movement of a joint actuated by air muscles is determined by distance between the attachment point and the pivot point. The smaller the distance, the longer the range of movement. A smaller distance also gives faster movement, less power and less resolution. A larger distance will give a smaller range of movement, with a slower speed and extra power and resolution.

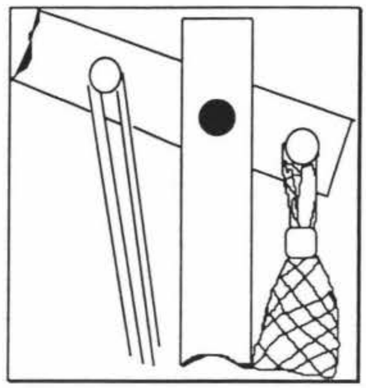

Figure 3-6: Air muscle being used to actuate a simple joint.

It was desired that the robot finger look similar to a human finger for aesthetic reasons. This meant that the simple lever form had to be altered to remove the protrusion at the back of the joint. This form also meant that there would be little position control over the joint when the two links were aligned.

Various designs were considered:

- the simple lever, which was discarded due to the necessity of having a lever protruding from the back of the knuckle.

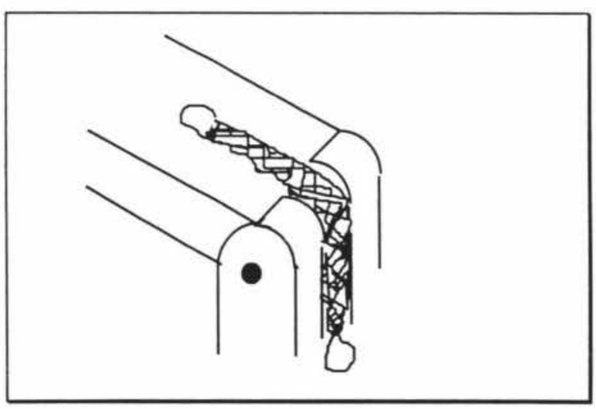

Figure 3-7: Door hinge joint.

- solid links with a door hinge type of joint and the muscles stretched around the joint (taking advantage of the special characteristics of the air muscle that enable it to work while bent), as shown in figure 3-7.

- A simple pin joint with two parallel links either side of the joint and a cylinder concentric with the joint to stretch the muscle around, as in figure 3-8.

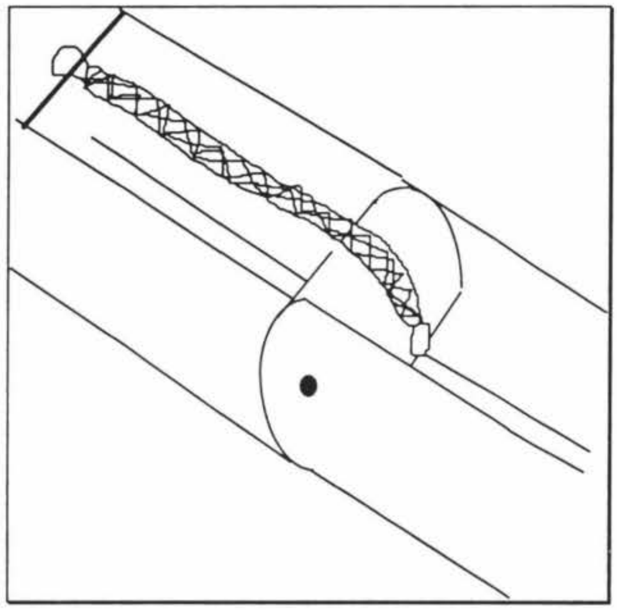

Figure 3-8: Pin joint with cylinder and two parallel links.

- A joint as in figure 3-8 except with the cylinder removed. This would remove any problems with stretching the muscles over a curved surface. In effect this gives a simple lever, but with the links made larger. This removes the protruding lever at the back of the joint by incorporating it into the link. This modified design is shown in figure 3-9.

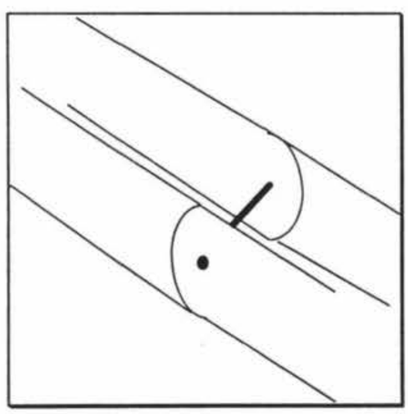

Figure 3-9: Modified pin joint with two parallel links.

The design in figure 3-9 was considered to be the best. The two parallel links would provide good stiffness for the finger and provide protection for the air muscles and sensors located in-between the links. Attachment points for the muscles would be easily provided by pins between the links. The muscles would be pulling in a straight line. There is no protrusion to snag on objects or look unsightly. The air muscles can be operated in antagonistic pairs or in combination with a spring to open the joint out. Using only one muscle per joint will mean less complexity for the intelligent controller and less overall system weight as fewer valves would be needed. However, due to the design goal that the hand has active compliance it was decided that antagonistic pairs of muscle be used, so that the joint could be actively controlled.

The links were desired to be made out of suitably light weight yet stiff material. For ease of use, cost and availability, lengths of 30 by 3 millimetres aluminium were used.

A modified potentiometer was added to the outside of the link for joint position feedback. For the prototype it was decided that ease of access was important and it is the intention to move the sensors to inside the links when they have proved their worth on the prototype. Figure 3-10 shows the potentiometer location and the modifications made to a standard trimming potentiometer for use in this application.

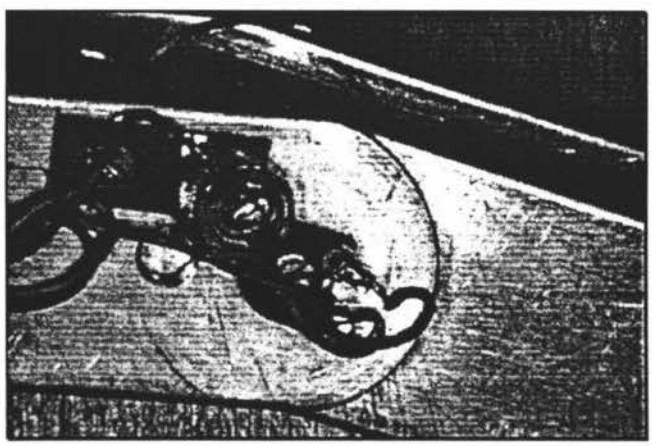

Figure 3-10: Robot finger potentiometer.

Six of the air muscles obtained from the Shadow Robot Project were measured to discover how much variation existed. These muscles were known as the 'mini muscle' in comparison to the standard muscle and the bigfoot muscle. 11 of the bigfoot muscles were also measured. The measurements are given in Appendix A.

The measurements showed variation in the mini muscles. However, the maximum stroke of the air muscles was an average of 17.5 millimetres. In order to allow the muscles to operate fully inside their effective range, a value of 16 mm was used for the stroke. For a desired joint movement of ninety degrees Pythagoras' theorem could be used to give a distance of 11.3 millimetres between the attachment point and the pivot point. This is consistent with the manufacturer's recommendation of "about one centimetre for a good range of movement."

As the desired range of movement is 90 degrees, the resulting force, speed of movement and resolution of the joint will have to be tolerated. Experimentation and analysis will show how a tradeoff should be made if one of the factors is to be increased at the expense of another.

The radial distance from the pivot point to the attachment point was lengthened slightly to be 12 millimetres, from the 11.3 millimetres calculated for a 90 degree range of movement to give slightly more force for a slightly reduced range of movement of about eighty five degrees. Using the average inflated and deflated length measurements for the muscles, the distal attachment point for the closing muscles can be calculated as being a vertical distance of 11 millimetres from the pivot point and a horizontal distance of four millimetres. As the range of movement is 85 degrees from fully opened to fully closed, the distal attachment point for the closing muscles can be calculated as being a vertical distance of four millimetres from the pivot point and a horizontal distance of 11 millimetres. The proximal attachment points were on the centre line of the link. Figure 3-11 shows the design in an assembly drawing.

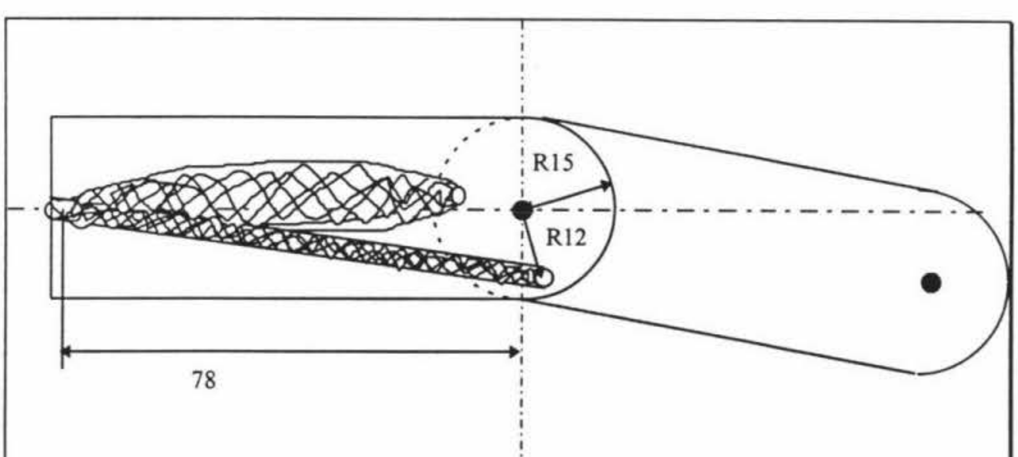

Figure 3-11: The joint design.

This joint design would be sufficient for the two distal joints but a different joint was needed for the proximal joint (the metacarpal-phalangeal joint in the human hand).

3.5.4 The Design of the Metacarpal-Phalangeal Joint

A design was desired where the axes of the metacarpal-phalangeal intersected, to avoid difficulties experienced by other robot hands in this area. It was also desired that the design would have circumduction, that movement in the human finger which enables full thumb-finger opposition.

Two types of joints to meet these design desires were considered. First, a ball joint, as shown in figure 3-12. When actuated by the air muscles this joint design has the problem that the air muscles have inherent compliance and hence the joint will sag with gravity. The addition of sensors could pose a problem also.

Second, a pivot point type of joint, as shown in figure 3-13. This type of joint is simpler than a ball joint, but has the same problems. In addition the pivot would be provided by a strand of metal or plastic and hence could suffer from fatigue.

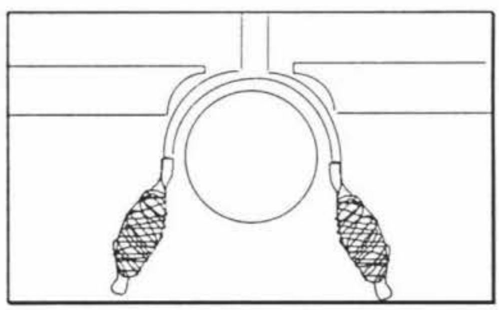

Figure 3-12: Ball design for metacarpal-phalangeal joint.

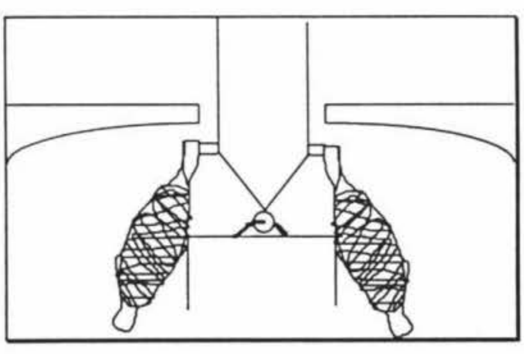

Figure 3-13: Pivot point design for metacarpal-phalangeal joint.

It was decided that initially a universal joint would suffice for the prototype, with other more complex alternatives to be considered at a later stage. A thirty degree yaw was needed and eighty five degree pitch as in the other joints. With this joint having to move the mass of the entire finger, it was elected to use two bigfoot muscles for the pitch and two mini-muscles for the yaw. With the reduced range needed for the yaw the mini-muscles would supply three times more power than in the pitch of the finger joints. Potentiometers were included in the joint so as to be able to measure the angle of both axes of the joint.

A universal joint was desired that had a 90 degree pitch and a 30 degree yaw. The design for this is shown in figure 3-14.

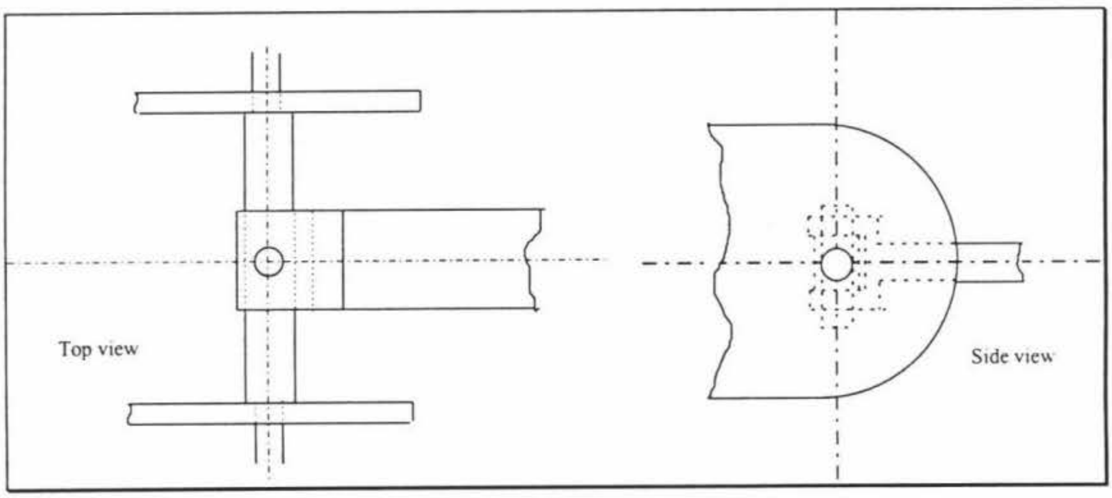

Figure 3-14: Universal Joint design.

With the universal joint design complete, a design was needed for the fingernail and fingertip.

3.5.5 Fingernail Design

In the human hand fingernails are very useful, providing a useful way to discriminate textures and manipulate small or thin objects. Nails also provide a rigid backing and protective sheath for the human finger, not such a large consideration for a robot finger made out of metal.

A fingernail was to be added between the finger tip links. Another robot hand project [41] had a fixed thumb nail, which enabled the hand operator to pick up a thin metal rule. However, it was felt that the 2 centimetres long, 1.5 millimetres thick nail might interfere with grasps so a retractable thumb nail, which was actuated by a small motor, was added.

For the finger a thinner shorter nail would be of use without getting in the way, in the same way as many humans have short but serviceable nails. The addition of a strain gauge to the nail could provide information about how much force being exerted on the nail. Taken over time the strain gauge could give information about the texture of the surface being scraped by the nail.

3.5.6 Fingertip Design

Research is proceeding [[42], [43]] on manipulation using soft fingertips, of semi-active and passive designs. Some current robot hands, such as the Salisbury hand, deliberately use hard contact at the fingertips to make the control easier. Other researchers are investigating soft fingertips to determine if increased control complexity is worth better operation. The softness of the human fingertip can be of considerable use in grasping and manipulation. At other times, when examining the marks left behind by the strings of a guitar, harder fingertips are wished for. The human fingertip will ingeniously toughen the layer of skin on the fingertip by adding a callous. People who constantly perform hard manual labour involving grasping shovels or ropes will also develop callouses. After a period of time when the grasping or guitar playing is ceased the callouses will be shed.

At this point solid fingertips will be used, in order to give a basis for further testing. An Interlink Electronics Force Sensing Resistor will be used for tactile sensing. This sensor converts a touch of an object into a variable resistance. Should this sensor prove successful in the fingertip, arrays of the sensors will be located over the whole finger, to provide a sensor every two to three millimetres, similar to the human finger.

The design of the fingertip gives the final component in the design of a whole finger combining the fingertip, two phalangeal joints and a metacarpal-phalangeal joint.

3.5.7 The Design of the Whole Finger

The design of the prototype finger was a matter of taking the components designed in the previous four sections and combining them together in such a way as to meet as closely as possible the PTIRH specifications given in section 3.2.

3.5.7.1 Joint and Link Naming Convention

By convention, the joints were named Joint0 (the metacarpal-phalangeal joint), Joint1 (the first or proximal phalangeal joint) and Joint2 (the second or distal phalangeal joint). This lead to the links being known as Link0, Link1 and Link2. The pivot points are known as Pivot Point0, Pivot Point1 and Pivot Point2. To confuse the issue slightly, the muscles to actuate Joint2 will be proximally attached on Link1 and distally attached to Link2. The proximal attachments for the muscles actuating Joint0 will be on the palm. Figure 3-15 shows a diagram of the convention.

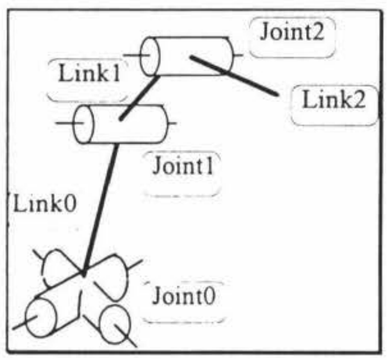

Figure 3-15: Joint and link naming convention.

3.5.7.2 Integration of Finger Components

One way to slightly reduce the distance between the joints is to put the muscles on an angle to the edges of the links. The muscles used to close the finger could be attached at the proximal end close to the outside of the finger and angled down to their distal attachment point. However, allowance needs to be made for the proximal attachment point of the opening muscles. The loops used to attach the muscles allow a three millimetre diameter rod to be inserted and then there has to be at least two millimetres between the rods, which are tapped and screwed into the links from the outside. Ideally the muscles would stay in the space between the links and not bulge out when inflated.

From the data in Appendix A the maximum inflated diameter of the mini-muscles is 11.25 millimetres with a one kilogram load. Therefore the attachment points for the opening muscles should be centred a minimum of six millimetres from the edge of the link. The centre of the closing muscles' proximal attachment point must therefore be a minimum of 8.5 millimetres from the edge of the link.

By using the distal attachment points of the muscles actuating Joint1 as the proximal attachment points for the muscles actuating Joint2, and from the distal attachment points given in section 3.5.4, the distance between Pivot Point1 and Pivot Point2 can be reduced to 78 millimetres. The attachment points meet the minimum distances in the preceding paragraph. This method also means the finger will be less complicated and have fewer parts, saving weight and cost.

The length of Link2 was set to 60 millimetres from Pivot Point2, a length designed to mimic the shorter fingertip bone of the human finger.

To exert enough force to move both Link2 and a load, a pair of muscles operating antagonistically was used. However, Joint1 would have the load, the weight of Link2 and the weight of Link1 to move. It was decided that Joint1 would have a pair of muscle pairs operating antagonistically. The only effect this had on the design was to make the distance between the two sides of the links greater. Each muscle needed 9 millimetres in width, so with the four muscles of Joint1 all attached to one attachment point the two sides of Link0 had to be at least 36 millimetres apart. Link1 fits inside Link0, with Link2 inside Link1, as shown in figure 3-16. This meant that the three millimetres of each side of Link2 plus two polyethylene washers of 0.5 millimetres also had to be taken into account. This gave a total of 43 millimetres between the two sides of the links, which is the length of the attachment rods.

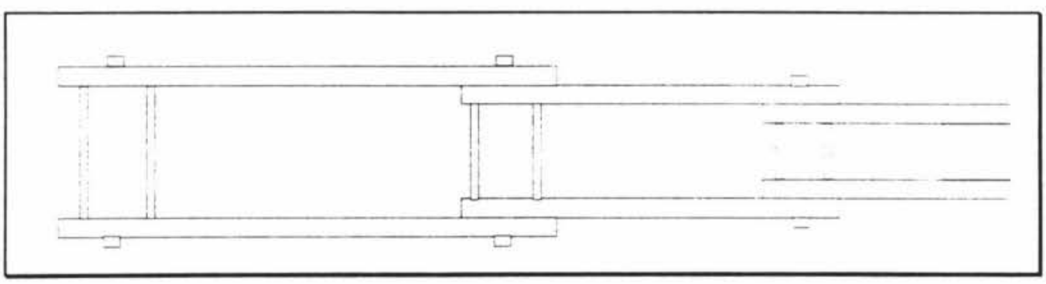

Figure 3-16: Top view of the finger showing the nested link arrangement.

The distal attachment points for Joint0 were different from those for Joint1 and Joint2, due to the bigfoot muscles being used for the pitch, as the distance between the distal attachment point and Pivot Point0 is dependent on the stroke of the bigfoot muscle. This meant the method used for calculating the attachment points on a 30 millimetre wide piece of aluminium was not valid, as the attachment point was going to be on a radius greater than 15 millimetres. A compromise was made in the ideal angle of the attachment point from the pivot point so the attachment point for the two bigfoot muscles could still be on Link0. This resulted in the muscles protruding past the palm when inflated (as shown in figure 3-17), but this was not thought to be a problem at this stage.

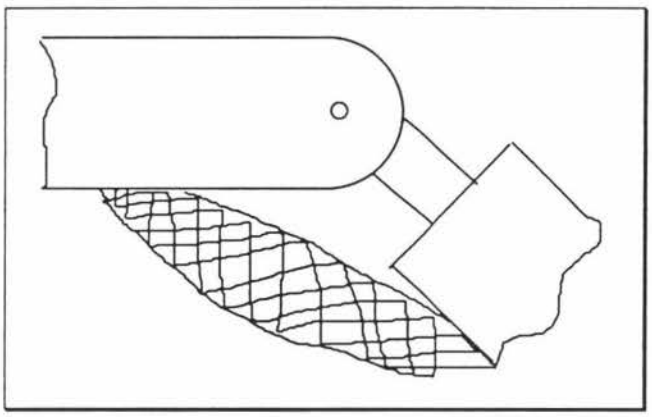

Figure 3-17: Side view showing the inflated bigfoot muscle appearing.

Finger drawings are located in Appendix B. Having designed a finger, two components of the hand remain: the palm and the thumb joint. The palm design is discussed in the next section.

3.5.8 The Design of a Palm on Which to Base the Finger

The palm has four important functions in PTIRH. First, the palm serves as a structural base on which to mount the fingers, thumbs and a wrist. Second, the palm provides a region for the air supply lines to the air muscles to pass through. Third, the palm provides a surface for the fingers and thumbs to grasp against in power grasps and will have sensors added at some point to aid in power grasps. Fourth, the muscles which move the universal joints of the thumbs and fingers are attached to the palm.

The fingers and thumbs were located in line and 150 millimetres apart so as to make opposition grasps as easy as possible. The fingers were located 100 millimetres apart between centres to give them room to move, without being too far apart. This gave the palm a width of 150 millimetres. The length of the palm was decided mainly by the attachment points for the bigfoot muscles, which was 250 millimetres from the universal joint of the fingers. Another 50 millimetres was allowed for an attachment device to connect to the ASEA robot, making the whole length of the palm 300 millimetres.

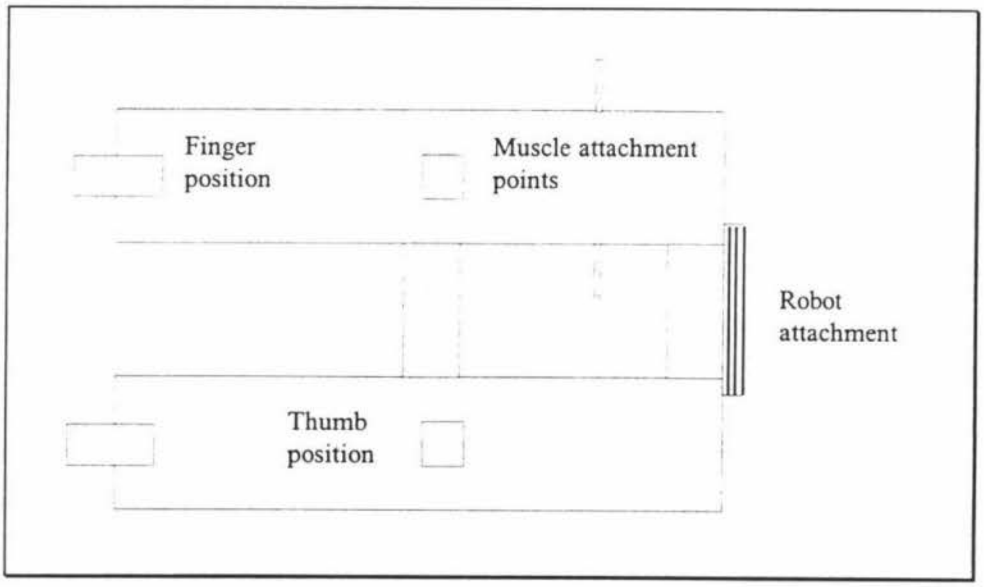

Figure 3-18: The palm design

Consideration was given to curving the surface of the palm to aid in power grasps, but for ease of construction of the early prototype, the palm was left as simple as possible. The design of the palm is shown in figure 3-18.

3.5.9 The Design of a Thumb Joint

The joint at the base of the thumb differs from the joint at the base of the finger by having a roll axis of 180 degrees instead of the yaw axis of 30 degrees. The pitch axis is the same. To allow for movement of the roll axis the joint is mounted 30 millimetres above the palm. Figure 3-19 shows the thumb joint design.

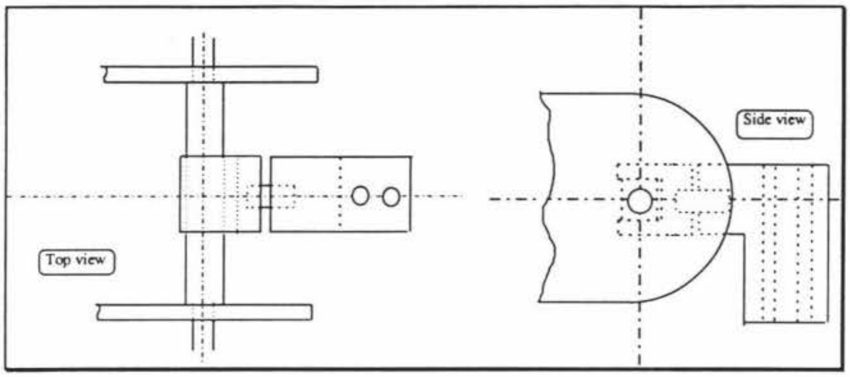

Figure 3-19: Thumb joint design

3.6 Implementation and Development

3.6.1 Introduction

With the completion of the mechanical design of PTIRH the next step was the implementation of the design. In keeping with many other robot hand projects it was decided that initially a single prototype robot finger would be built to test the robot finger design and evaluate how successful the air muscles would be as actuators for the robot hand. As PTIRH's fingers and thumbs were of nearly identical construction, the lessons learnt from testing would be easily transferable. The addition of sensors would provide the feedback for an intelligent control system, which is yet to be developed. To demonstrate the concept behind the novel configuration of PTIRH, the other digits and the palm would be constructed, but have no actuation installed.

Section 3.6.2 discusses the construction and development of the finger and section 3.6.3 outlines the construction of the whole early prototype hand.

3.6.2 Construction of PTIRH's Finger

Aluminium was chosen to make the links out of, as it is light, easily workable, will not corrode and strong enough. Mechatronics Technician Ken Mercer constructed the finger as specified by the design drawings given to him. The construction of the robot finger began with the finger tip. Initially the finger tip was not built as designed, but as a simple piece of cylindrical plastic, for simplicity. The fingernail could be easily added at a later stage for texture discrimination.

The fingertip was quickly built and Link1 was constructed. The joint to connect the two, Joint2, was then begun. The design was shown to have some problems, as the attachment points were located such that an inflated muscle passed through the pivot point of the joint, which was provided by a tapped pin with a screw to hold the links. Bushes were added to each side of the link so that the pivot did not need a pin right across the width of the finger. Polyethylene washers were used to reduce the friction in the joint. This design meant that the muscles could now be attached. However, due to the overlapping links it was now impossible to screw the muscle attachment pins in. To rectify this, two holes were drilled in each Link1 to allow countersunk screws to be fitted for the muscles attachment pins, which were now also serving as spacers for the links. LinkO and Joint1 were constructed. Potentiometers were added to Joint2 and Joint1.

Mechatronics Technician Steve Schaare constructed the universal joint for the base of the robot finger to the specifications given. Potentiometers were added to both axes.

Steve Schaare also constructed new spacers so that two pairs of muscle pairs could be used to actuate Joint1. The initial design was only wide enough to allow two muscles to actuate the joint in an antagonistic configuration and it was decided that this joint would need more force to actuate it than Joint2, hence the modification. Figure 3-20 shows the detail of Link0, where the two pairs of muscles operating Joint1 can be seen. Figure 3-21 shows the detail of Link1.

3.6.3 Construction of the Early Prototype Hand

The other finger and the two thumbs were constructed by the author and Mechatronics Technician Steve Schaare. The modular design proved its worth here, as all three digits were constructed identically, right down to the universal joints. This was a slight error, as the design for the universal joints of the thumbs had a roll axis instead of the yaw of the fingers. However, a roll axis was easily added, and so the thumb base joints ended up with three axes of movement, giving them a larger work envelope than originally designed. This is not a bad thing at all, it only remains to see if this joint can be successfully actuated. The modular design speeded up the construction considerably and meant that parts were interchangeable.

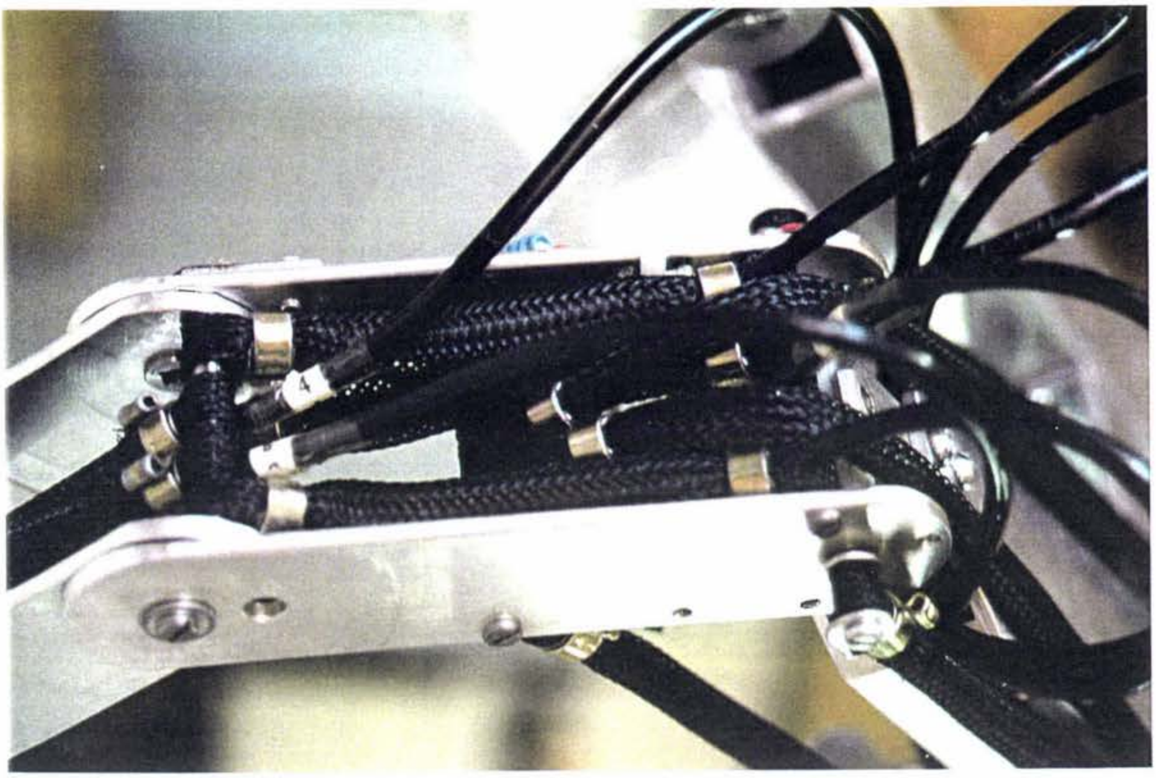

Figure 3-20: Detail of link0

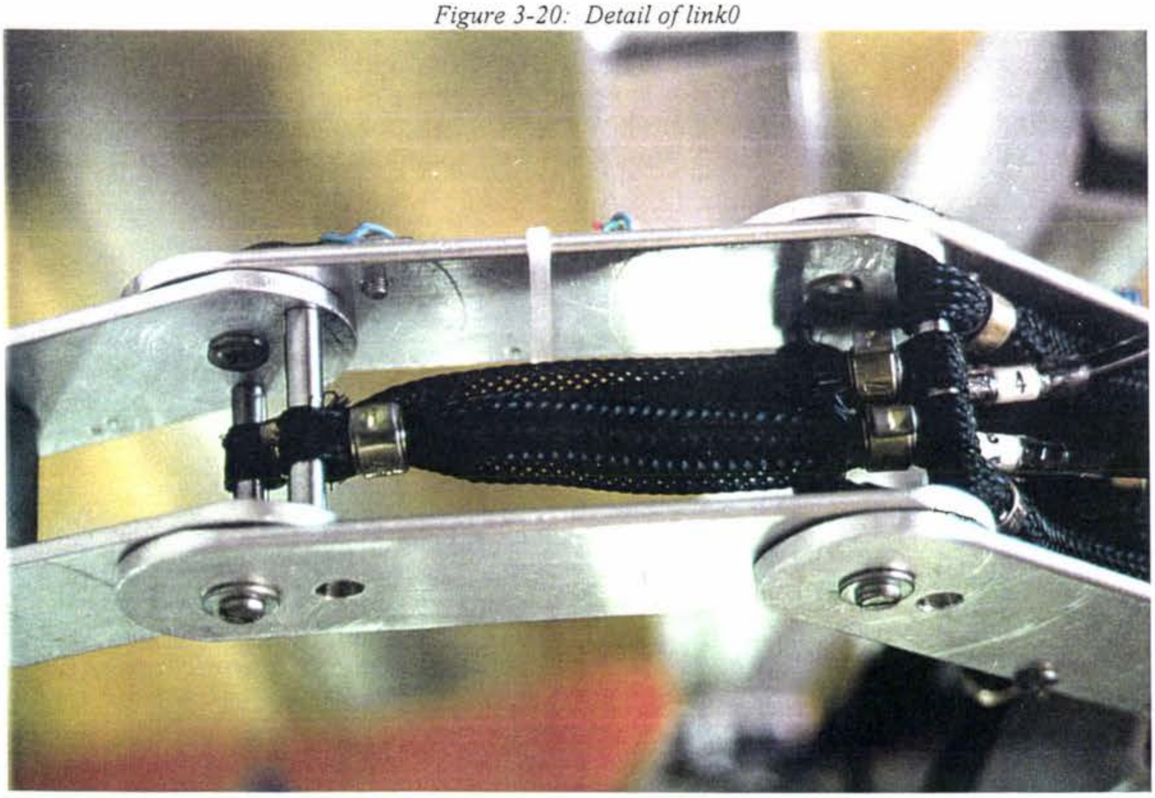

Figure 3-21: Detail of link1

The palm was built out of two pieces of RHS (rolled hollow section) aluminium, muscle attachment points added and a connection for the ASEA robot arm installed. The digits were screwed on and the end result is shown in the figures below. Figure 3-22 on page 65 shows the early prototype robot hand mounted on the ASEA robot and figure 3-23 on the same page shows a top view. Figure 3-24 on page 66 shows a bottom view and on the same page figure 3-25 gives a side view.

3.7 Conclusions

The design goals for PTIRH were given. These goals were: to be able to manipulate large objects and assemble small components; have two fingers and two thumbs, each of four degrees-of-freedom; weigh less than 3.8 kilograms; be of modular design; be intelligent and be a test bed for many different types of sensors; be as close to human hand size as possible, but suitable applications will be able to be found if this is not the case; be similar in performance to the human hand; be actively compliant; and be of low cost.

Although the goals of the design are specific enough the process of designing a hand to meet these goals is difficult. The hand is made up of many components and the intelligent hand project is made up of sub-projects, thus the only way to establish if the goals are met will be when the hand is built and operational. This means that the design of the hand proceeded with only a little analysis and calculation and is based mainly on engineering judgement and experience.

A prototype robot finger was constructed. There will be experiments carried out on the prototype. Once this is built a second version of the robot finger will be built, incorporating the knowledge learnt from the prototype. This is not to say the prototype itself will not be very successful, but rather that there will be things that could be changed to make the finger work better. It may be that it will be desired for the dexterity of the hand to be improved at the expense of its strength or vice versa.

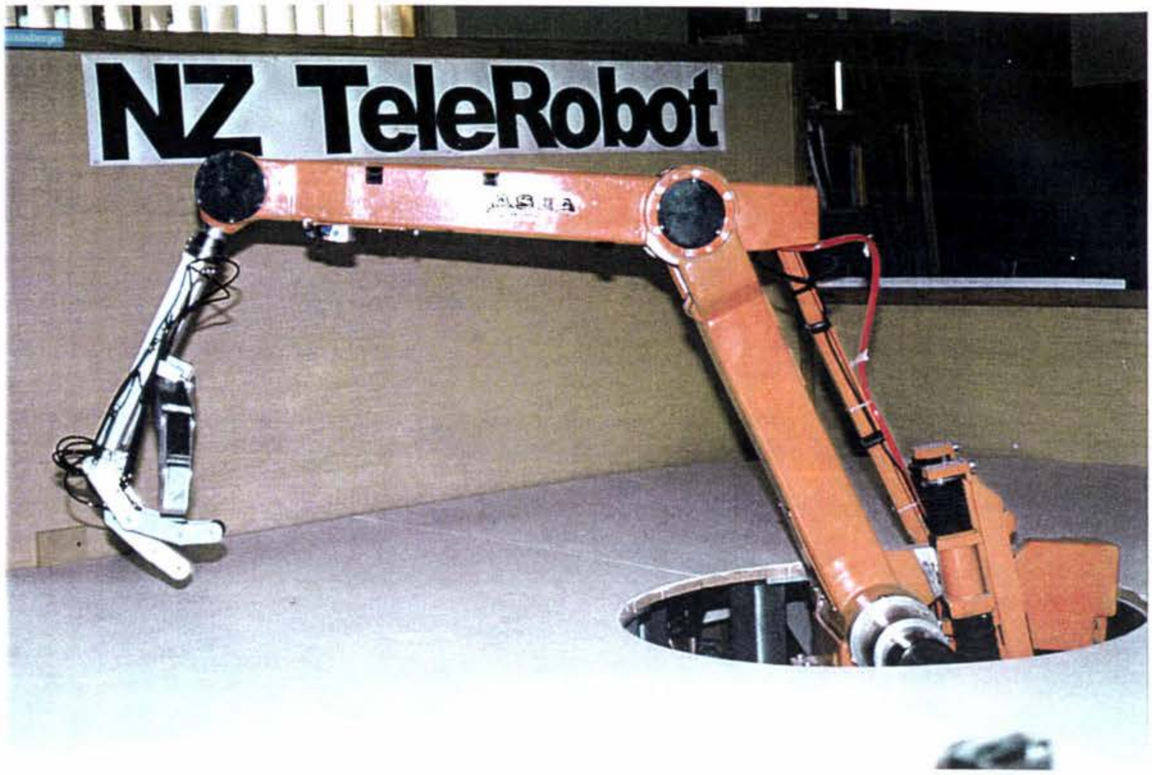

Figure 3-22: The early prototype robot hand mounted on the ASEA robot

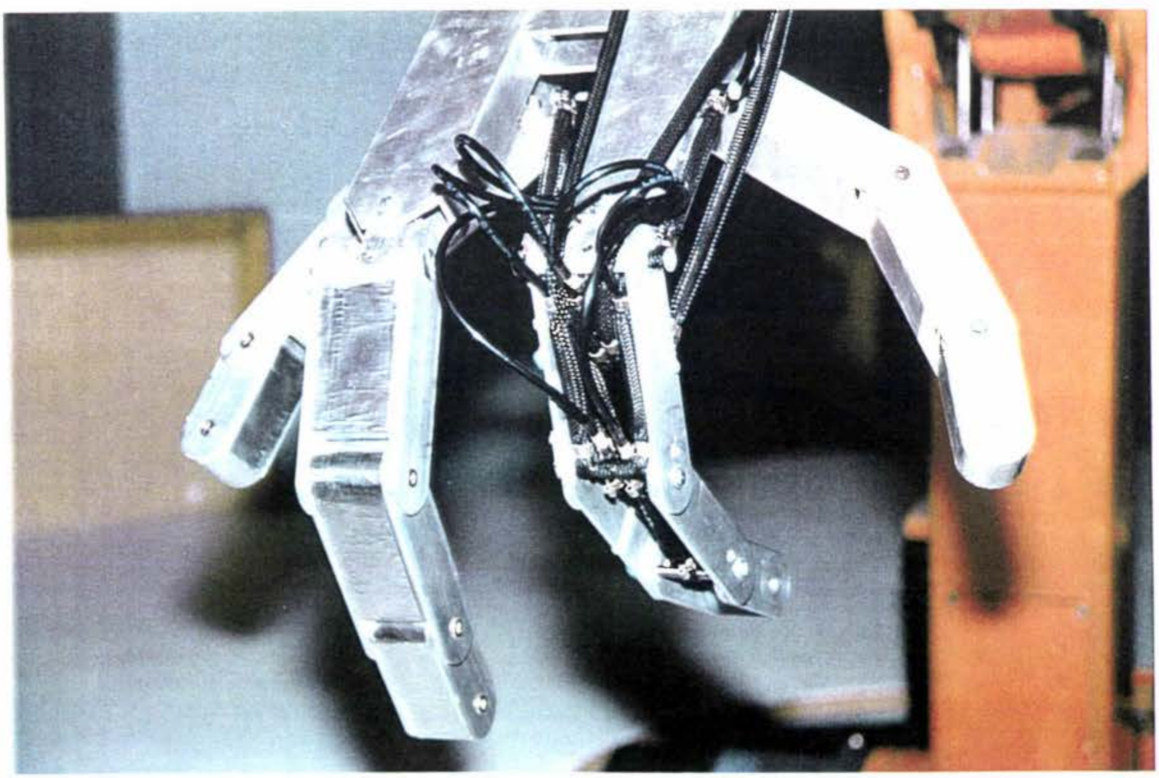

Figure 3-23: Top view of the early prototype robot hand

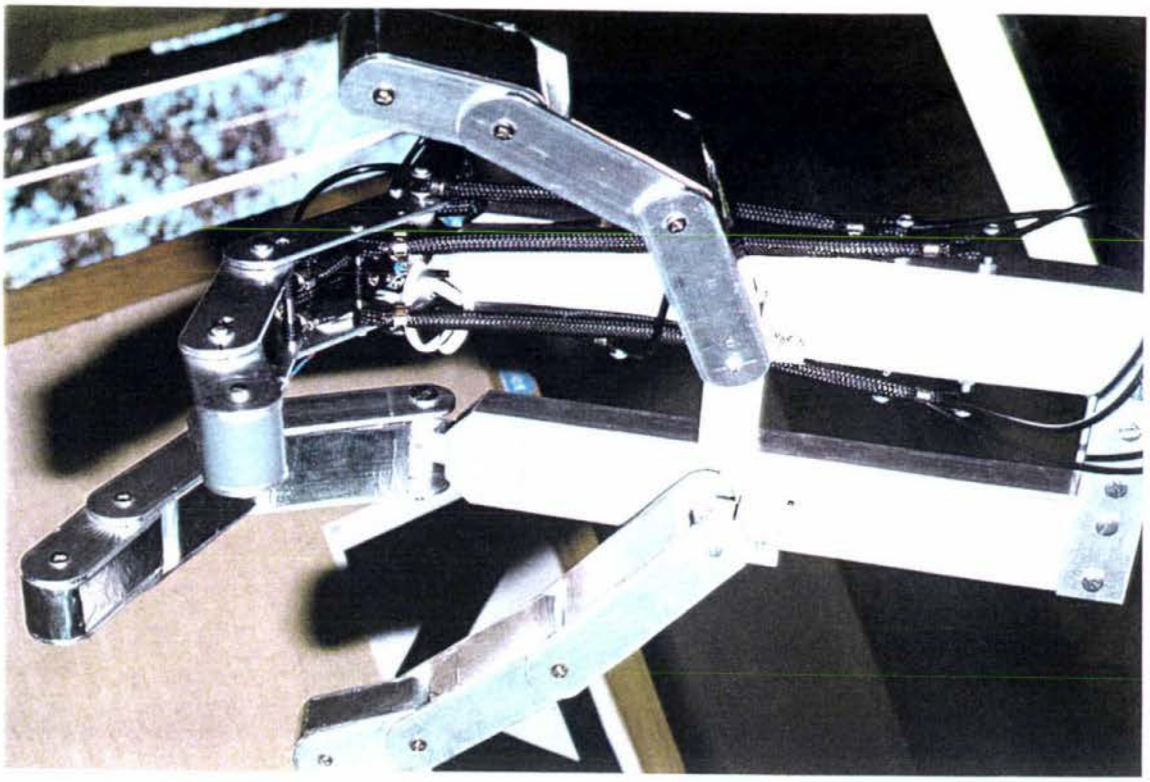

Figure 3-24: Bottom view of the early prototype robot hand

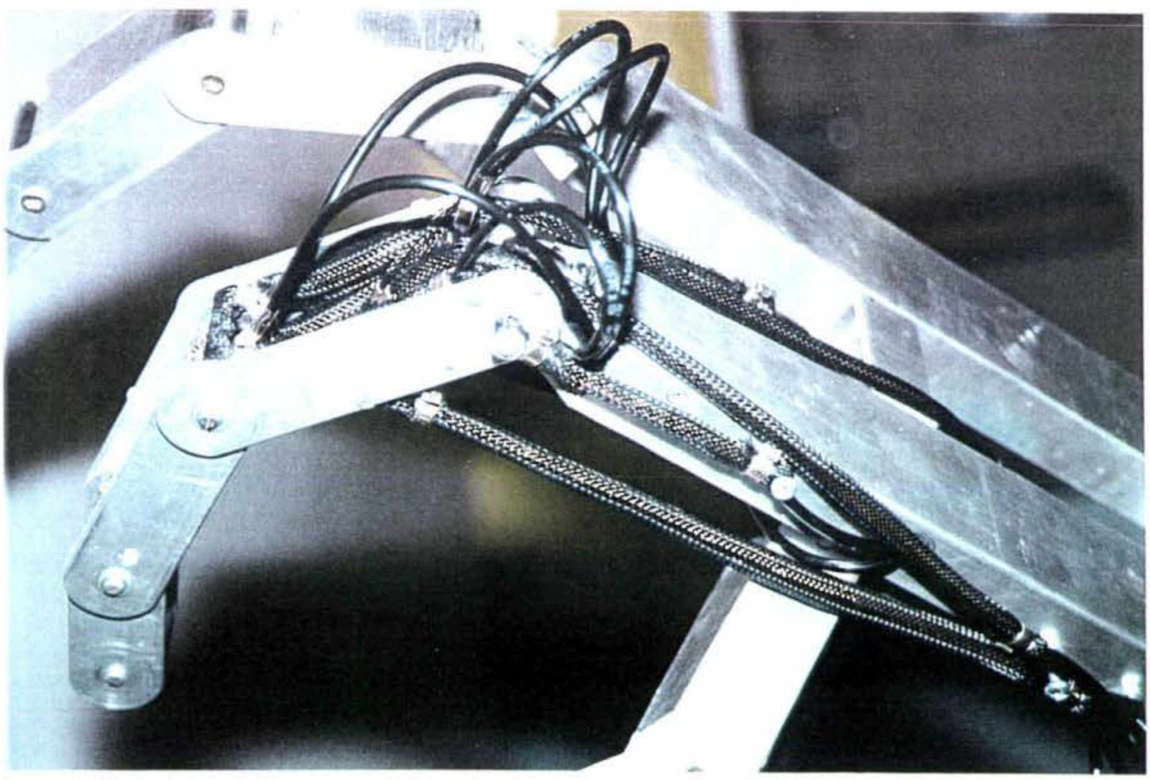

Figure 3-25: Side view of the early prototype robot hand

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Chapter 4

EVALUATION, RESULTS AND DISCUSSION OF PRODUCTION TECHNOLOGY'S INTELLIGENT ROBOT HAND

4.1 Introduction

This chapter is an evaluation of the concept of the Production Technology's Intelligent Robot Hand, and of the components of the hand that have been designed and built. It reports on the capabilities of the prototype robot finger with actuators that was built and discusses the implications of these capabilities on the PTIRH concept. The testing of the air muscles and their application as actuators for a robot finger is given, as are the results of testing of the servo pneumatic valve. Evaluation of the sensors installed on the finger is made. The early prototype hand demonstrates the grasps that are possible with a robot hand that has two thumbs and two digits. An evaluation of the concept of PTIRH is made.

The evaluation of a prototype such as the modular finger is a cyclical process. The initial version of the prototype is constructed from the design drawings, with some modifications made to the design on the spot if the design proves unable to be realised. Testing is carried out on the prototype to see if the desired performance was achieved. Solutions to any problems are found. Modifications are made to the prototype and the performance testing repeated to find if the modifications resulted in the desired improvements.

The material in this chapter has been collated into a logical sequence of experiments on each component to establish the capabilities of the components and of the whole PTIRH concept. Section 4.2 has an overview of the evaluation process. Evaluation of the sensors installed on the finger is made in section 4.3. Section 4.4 outlines the evaluation of the servo pneumatic valve. Section 4.5 gives the results of the evaluation of the air muscles' suitability as robot hand actuators. Section 4.6 evaluates the PTIRH concept. Section 4.7 concludes this chapter.

4.2 Overview of Evaluation

PTIRH is a system made up of the 'bones', or mechanical system, the actuators, the sensors, the control system and the 'muscles', or air muscle actuators. The control system will give PTIRH its intelligence and without it, it is very difficult to evaluate PTIRH's performance. Instead the evaluation will be carried out on each component of the system and the results extrapolated to the overall system.

The evaluation of the two thumbs, two fingers concept was carried out at an early stage of the project. These showed it was worthwhile completing the design process using this concept. An early prototype hand was constructed to aid in demonstrating the concept.

Evaluation of the air muscles in their novel use as the actuators for a robot hand was also begun early, and has continued throughout the course of the project. They have proved versatile actuators with some limitations.

One of these limitations is the necessity to have a valve to control the air muscle pressure. Evaluation of suitable valves resulted in a project to design and construct a servo pneumatic valve using the resources, students and technicians of the Production Technology Department. The valve has gone through a series of modifications but these have yet to result in a valve suitable for use with the mini-air muscles being used in the modular finger prototype. However, another department project utilising rodless pneumatic rams in modular automation has successfully implemented the valves to control the end position of the rams.

Evaluation of sensors for use with PTIRH was begun early on and is continuing with the development process of the modular finger prototype. The use of potentiometers for joint angle has proved successful, but issues such as calibration and wear have not yet been explored. The air muscle pressure sensors are providing feedback to a valve control algorithm implemented on a microcontroller. The force sensor has not had its capabilities fully explored.

4.3 Evaluation of the Sensors

Two of the three sensors chosen for PTIRH were implemented on the prototype robot finger. These were the pressure sensors and the position sensors. Two different types of pressure sensor were trialed: a capacitive based sensor and a strain gauge sensor. Potentiometers were used for the position sensors.

4.3.1 Pressure sensors

The pressure sensors were used to give feedback to the valves controller. This controller used a simple form of control known as "bang-bang" control. Figure 4-1 shows the flow diagram for the bang-bang algorithm and the program listing is in Appendix C. The desired pressure of the air muscles is set and the air pressure decreased or increased to reach the desired pressure. Readings are taken of the actual pressure via the pressure sensor. When the desired pressure is equal to the actual pressure, the valve is shut off. With a fast acting valve, good results can be obtained and there will not be too much overshoot.

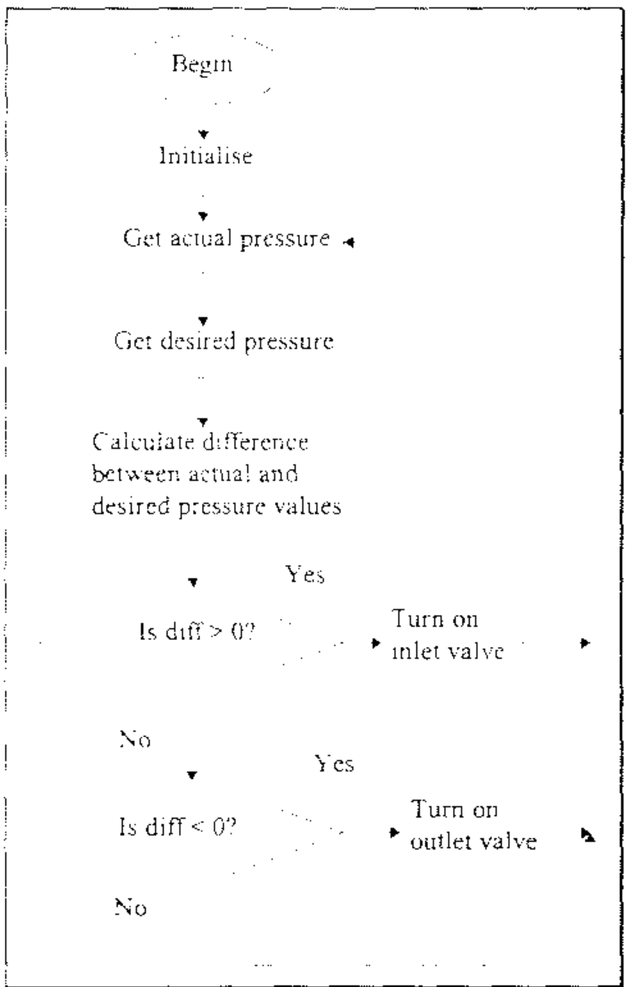

Figure 4-1 : Bang-bang control algorithm

Both the capacitive and strain gauge pressure sensor performed adequately in this application. An advantage of the capacitive sensor over the strain gauge sensor is that the output voltage can be sent directly to an analogue-to-digital converter, whereas the strain gauge sensor needs an amplifier circuit. There are eight valves needed for each finger, each valve requiring one pressure sensor. Therefore the extra circuitry becomes significant. The strain gauge sensor was also more expensive than the capacitive sensor owing to the need to buy a strain gauge bridge, whereas the capacitive sensor was merely high tolerance machining.

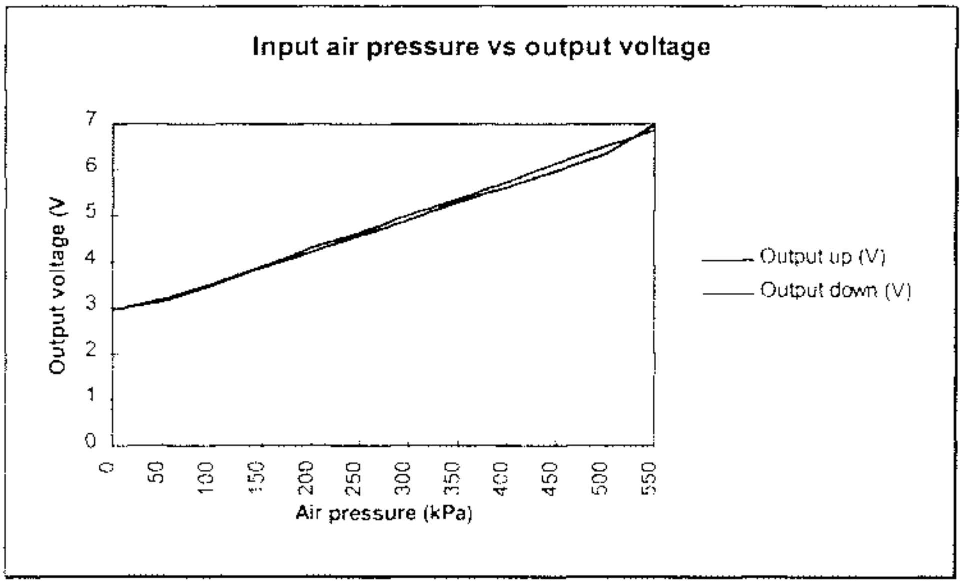

Figure 4-2: Output voltage of strain gauge pressure sensor

Experiments were performed on both sensors to determine their output characteristics. Figure 4-2 shows the graph of the output of the strain gauge sensor and Figure 4-3 shows the graph of the output of the capacitive sensor.

From the graphs it can be seen that the strain gauge sensor has a more linear response and a greater range of output than the capacitive sensor. This is the amplified output, however, whereas the capacitive output is unamplified.

The capacitive sensor was chosen as the pressure sensor for the servo pneumatic valves as it did not need the amplifier circuits and was of lower cost.

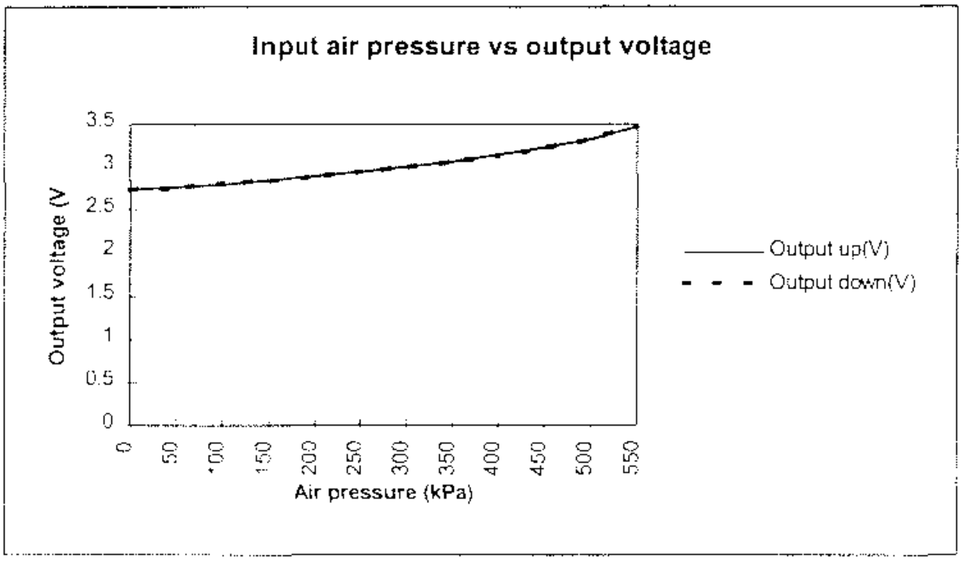

Figure 4-3 Output voltage of capacitive pressure sensor

4.3.2 Position sensors

The potentiometers chosen to be implemented to detect the change of joint position were standard 47 kiloOhm trim pots. These were disassembled and the resistive film attached to the bushing of the distal link. The wiper was attached to the proximal link of the joint, so that when the joint moved, the wiper moved on the resistive film.

A program was written for the Motorola 80C552 microcontroller that took the analogue output of the potentiometers for Joint2 and Joint1 and converted it to digital. The listing of this program is in Appendix C. This was a ten bit conversion, so a output of zero was equivalent to zero Volts and 1024 was equivalent to five Volts. As can be seen in Figure 4-4 and Figure 4-5, hysteresis was present in the results. This was probably due to friction in the joints so that when the pressure was released in the air muscle the joint position did not return as far as it should have.

From the graphs, it can be seen that there is a deadband where a change in pressure results in no joint movement. This is a property of the air muscles, where they do not start to contract until the inflatable rubber tube has started to press against the outer tube of nylon mesh, even when initially stretched.

From these results the potentiometers are effective at measuring the position of the joints.

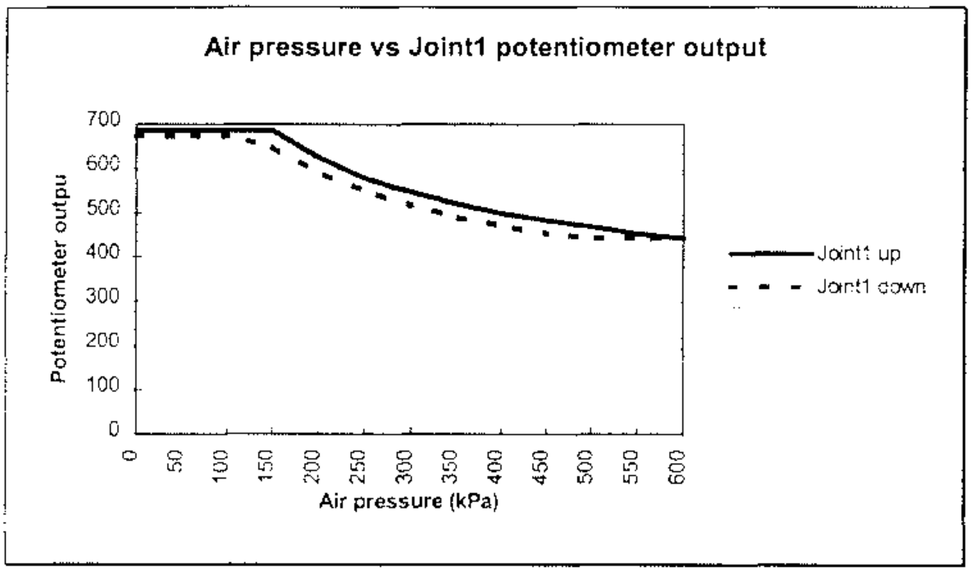

Figure 4-4: Output of the Joint1 potentiometer

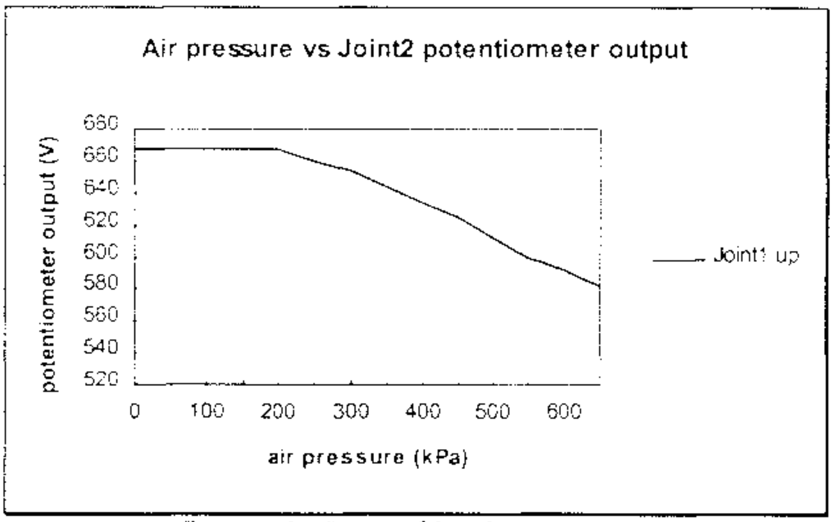

Figure 4-5: Output of Joint2 potentiometer

The potentiometers could have problems with the wiper and resistive film wearing and hence their properties may change. An initialisation operation may therefore have to be performed to ensure that the output of the potentiometers at a specified home position is correct.

4.4 Evaluation of the Servo Pneumatic Valve

Initial tests on the modified servo pneumatic valve showed it to have a response time of five milliseconds for the inlet solenoid valve to open at a supply voltage of 16 Volts. This is considerably faster than similar valves available commercially, which had time delays of around 20 milliseconds when the valve project was initiated [1]. This time delay corresponds to a switching frequency of 100 Hertz, which is fast enough to control the muscle. However, the valve was letting in too much air into the muscle for each pulse. Two 10 milliseconds bursts would completely fill the bigfoot air muscle, which has a volume of 19 cubic centimetres. The fly spray valves unit had very small apertures to give a misting effect in the fly spray application, whereas the apertures of the valves in the single unit were two millimetres in diameter. The apertures were obviously too large and needed reducing. The valve was also leaking through the join in the different sections and the inlet valve was leaking through the valve seat. The valve seat leak was such that the muscle would completely fill over a period of five seconds, without opening the inlet valve.

A plug with a one millimetre aperture was tapped into the two millimetres aperture. Gaskets were added to stop leaks through the section joins. The valve seat was modified to stop the leaking. Further testing showed the valve was still letting too much air through with each burst.

The diameter of the valve aperture was reduced to 0.5 millimetres. This again necessitated a change in the valve seat to take into account the smaller aperture. As the area of the aperture had been reduced by a factor of 16, this design was much more successful and the volume of air produced with each burst of air was considerably reduced. However, it still took only ten, ten millisecond, bursts to fill up the mini air muscle. This meant that each burst was still letting through too much air to achieve a resolution of one eighty-fifth of the stroke, which is necessary to achieve a joint resolution of one degree for a eighty five degree range of movement.

The performance of the valve had now increased to a point where at least eight intermediate mini muscle positions could be achieved, or a resolution of approximately ten degrees. Although it is desirable for this to be improved in the future, attention now turned to the control program for the valve in order to evaluate if the control theory would work.

Initially a simple bang-bang controller was used for the valve, as described in section 4.3.1. Owing to reasons explained above, the valve did not have a sufficiently small resolution to enable the air muscles to reach a steady state using this control program and so the air muscles oscillated around the desired set point, never reaching a steady state. The problem was that by the time the program had registered that the actual pressure was equal to the desired pressure and turned off the appropriate valve, a difference had occurred. A simple change was to pulse the appropriate valve for a set time and then perform the difference calculation. This meant the air pressure would not be changing while the calculations were being performed. More advanced control techniques, such as sliding mode, pulse width modulation and adaptive control, were implemented by another Masters student [2], but none could overcome the limitations imposed by the valves. Work is continuing on the valves to develop them to a point where they can be used for the mini air muscles.

The servo pneumatic valve has proved to be a successful design for conventional pneumatic cylinders using simple bang-bang control but has so far failed to live up to its promise in the application of the air muscles.

Future work on the valve will include a complete redesign of the valve, while still using the same concept; investigation into the possibility of reduce the air supply pressure in order not to operate the valve at its limits; and investigation in to different ways of implementing the valve controller. Presently, the valve controller is implemented in Microcontroller Pascal on a Motorola 80C552 microcontroller development board. It may be beneficial to program the microcontroller in Assembly language to achieve a faster response or to use a Digital Signal Processing board.

Should this work prove unfruitful, consideration should be given to looking at other methods of supplying the air muscles with compressed air.

4.5 Evaluation of the Air Muscles as Actuators for PTIRH

The advantages of the air muscles as actuators for PTIRH are greater than their disadvantages, as shown in table 4-1. The light weight of the air muscles meant that the hand could have a greater payload. The low cost of the air muscles at $9.60 each, which are imported from Britain, is an advantage for the project's limited budget and future commercial possibilities.

Advantages:	Disadvantages:
Lightweight	**Need for control valves**
Excellent power-to-weight ratio	**Mini air muscle too big**
Inherent compliance	
Novel actuator for robot hands	
Quick acting	
Potential for high resolution	
Reliable operation	
Low cost	
Good range of movement	

Table 4-1: Comparison of the advantages and disadvantages of the air muscles.

The power to weight ratio of around 400:1, compared to about 16:1 for DC motors and conventional pneumatic cylinders, is a large advantage for the air muscles over other actuators. The air muscles are inherently compliant and the active compliance of a pair of antagonistically operating air muscles can be controlled, which mimics the compliance of the human finger.

Disadvantages that have become apparent while using the muscles are that servo pneumatic valves have had to be custom designed and built (which have commercial possibilities). These valves now pose the problem of added weight. Because of this the valves have to be located on the forearm of the robot or even further away. This results in long air lines. The compressibility and the fluid properties of air will cause hysteresis, time lags, force reduction and control problems similar to the tendon and pulley systems of other robot hands. The smallest actuator is still quite large and has meant that the hand will be twice as big as a human hand, and so will find applications other than using human tools.

The advantages of the air muscles outweigh the disadvantages and so they will continue to be used until the decision may be made that their disadvantages are too great.

4.6 Evaluation of the PTIRH Concept

4.6.1 Introduction

The design goals for the PTIRH concept were given in section 3.2. These were what it was hoped PTIRH would be able to do, and the characteristics PTIRH should have. Limitation imposed by the state of the art, finances, time and choices made during the design process following the setting of the design goals, will have resulted in variations from the goals. This section evaluates how well the design goals have been met in the mechanical design drawings and the prototype modular finger which was built. The reasons for departures from the goals will be given.

4.6.2 Performance Tasks

PTIRH is to be used in assembly and material manipulation operations and it is desired it will be able to locate, orientate and grasp large objects. The design of the fingertips and fingernails should allow the grasping and manipulation of objects of any size, although at twice human size, the hand may experience difficulty with picking up small objects - this will depend greatly on the sensors used and their integration with the intelligent control system.

4.6.3 Hand Configuration

The hand configuration was chosen to be two thumbs and two fingers. This section lists the advantages it is perceived that a robot hand of this configuration will have over the configurations of other robot hands.

Two thumbs and two fingers would be able to apply equal forces on either side of a grasp and have equal gripping surfaces, equivalent to the standard parallel jawed gripper. As standard parallel jawed grippers are very common it will be good for PTIRH to be able to perform this operation.

The pulp pinch would have a larger pinch area with two thumbs in operation and consequently would be more stable and powerful or could be used to grasp two objects, as shown in figure 4-6.

A common grasp for robot hands is the fingertip point contact grasp and, as figure 4-7 shows, PTIRH will be capable of this grasp with both thumb-finger pairs.

A hand with two thumbs would have an advantage in most of the grasps and manipulations used by humans. For example, the power grasp would be made even more powerful and more stable with an extra thumb opposing the end finger. See figure 4-8 for PTIRH's version of the power grasp.

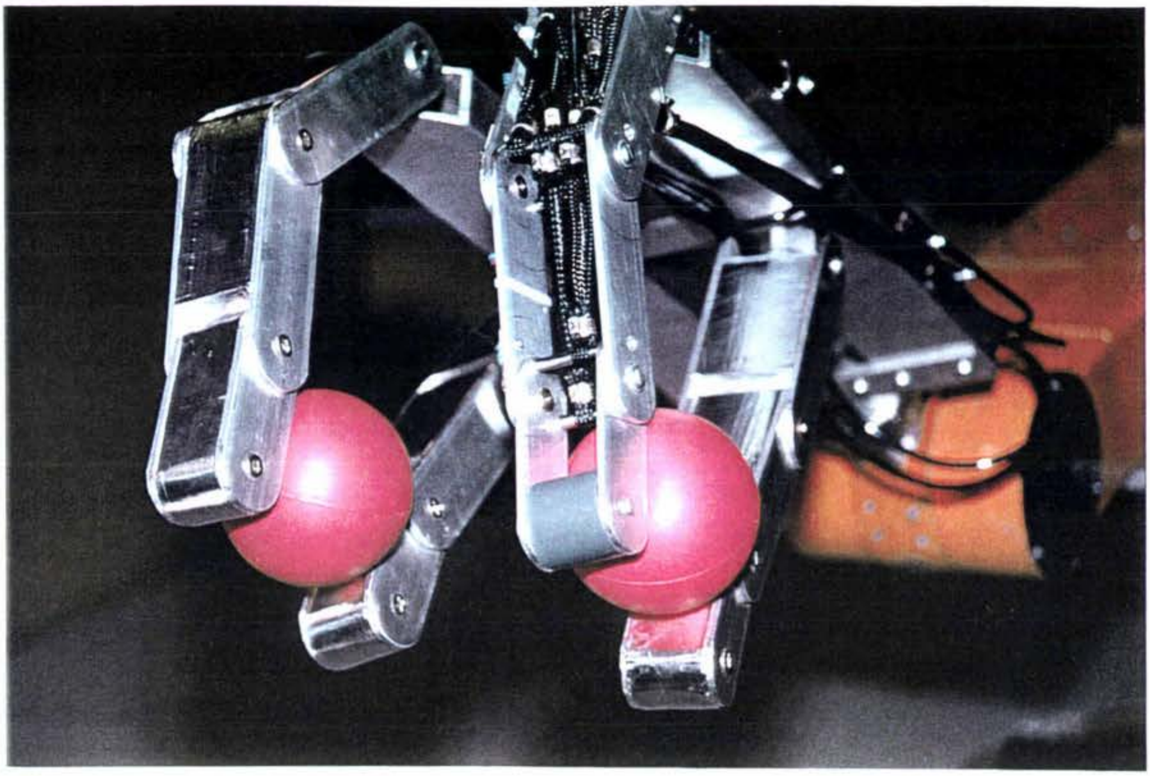

Figure 4-6: The pulp pinch with two thumbs and two fingers.

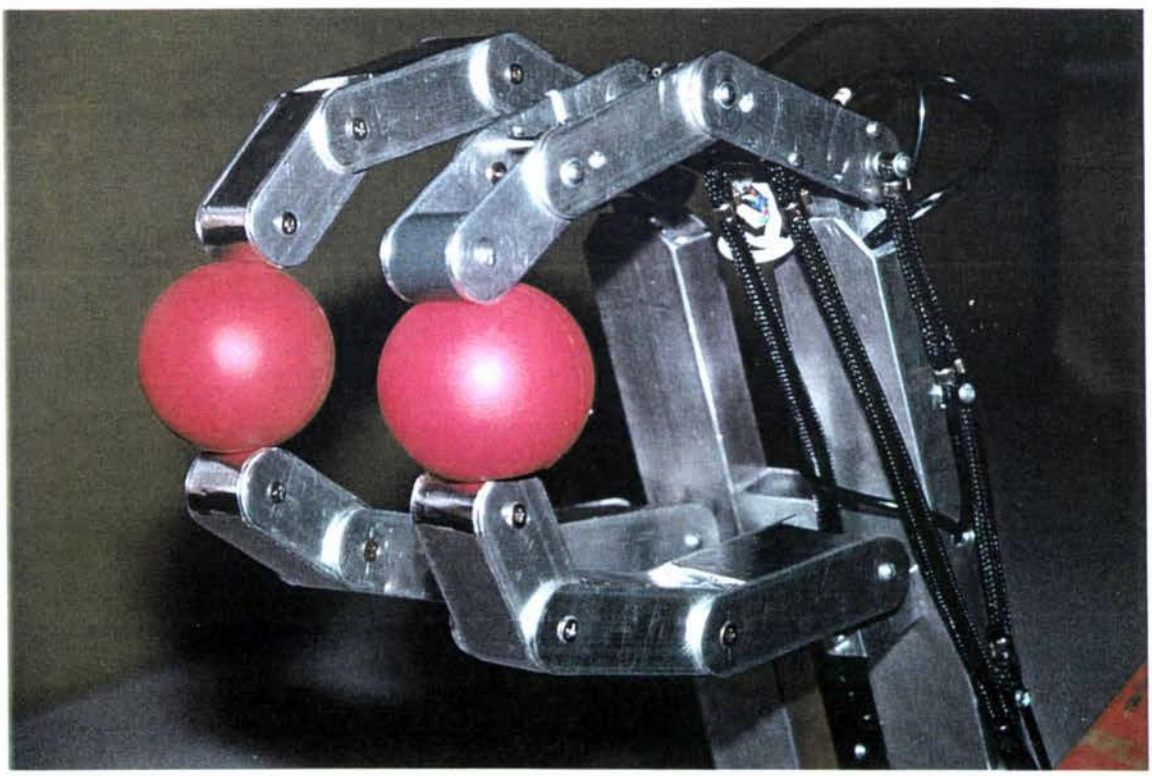

Figure 4-7: PTIRH's finger tip point contact grasp

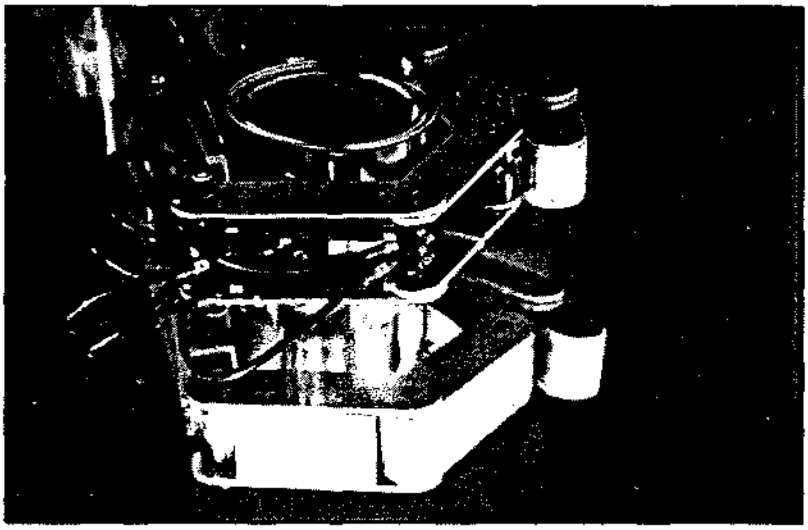

Figure 4-8: PTIRH's power grasp.

The spherical grasp would also be more stable. A common grasp, which is a combination of the tip pinch and the spherical grasp, is the three fingered grasp. With two thumbs this grasp would be even more stable and figure 4-9 shows PTIRH performing this grasp using four fingers.

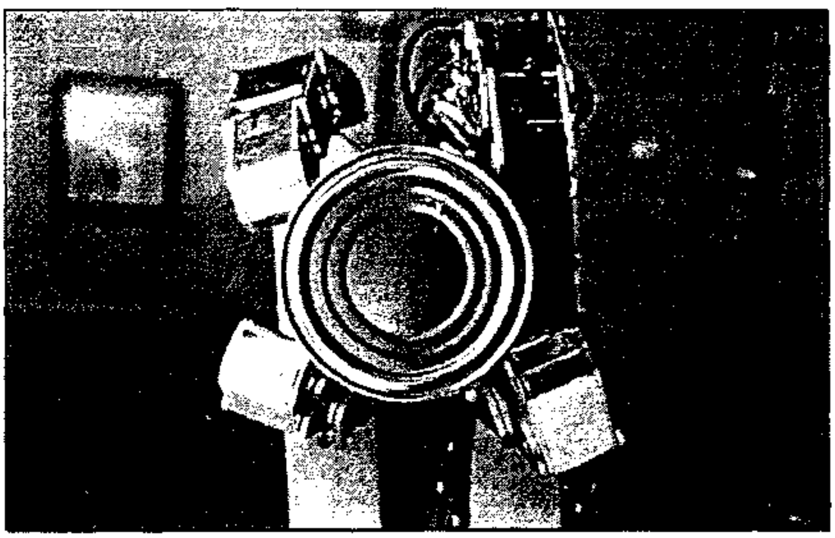

Figure 4-9: PTIRH performing the three fingered grasp with four fingers.

The writing grasp would not change, although it would be possible to hold two pens in the one hand, perhaps an advantage when alternating colours as it would not be necessary to swap pens. Figure 4-10 is of PTIRH using two pens to write.

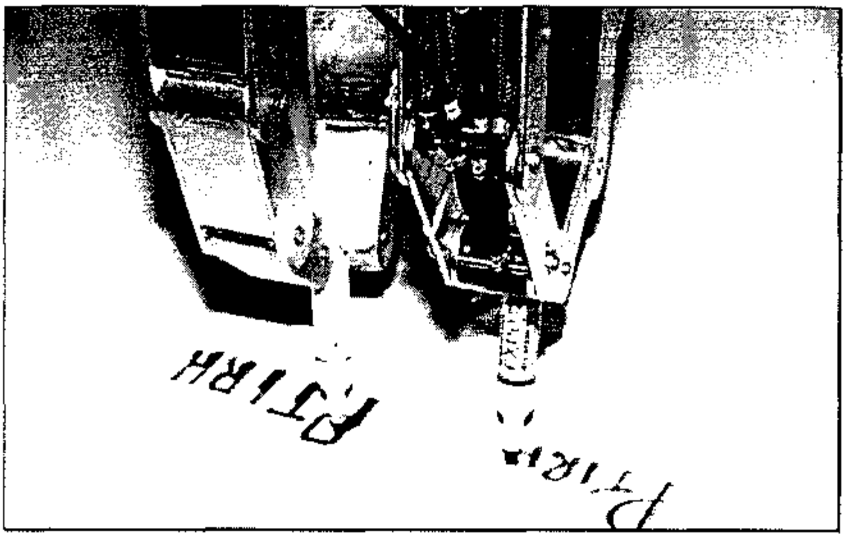

Figure 4-10: The writing grasp.

The lateral grip is a common grasp for picking up thin objects such as paper or proffering a plate. PTIRH would be a superb hand for a waiter, as it would be able to hold two plates in one hand, without the need for difficult balancing. Figure 4-11 shows PTIRH performing the lateral grasp.

The tweezers grip would not change as it does not use the thumb. This grip is not very often used, except by smokers and people wishing to pick up a small object out of a narrow container. People sometimes will make a scissoring gesture also. A projected use for an intelligent hand is part sorting, so this grasp, and the manipulation associated with it could become an important grasp in the PTIRH's array of grasps, as figure 4-12 shows.

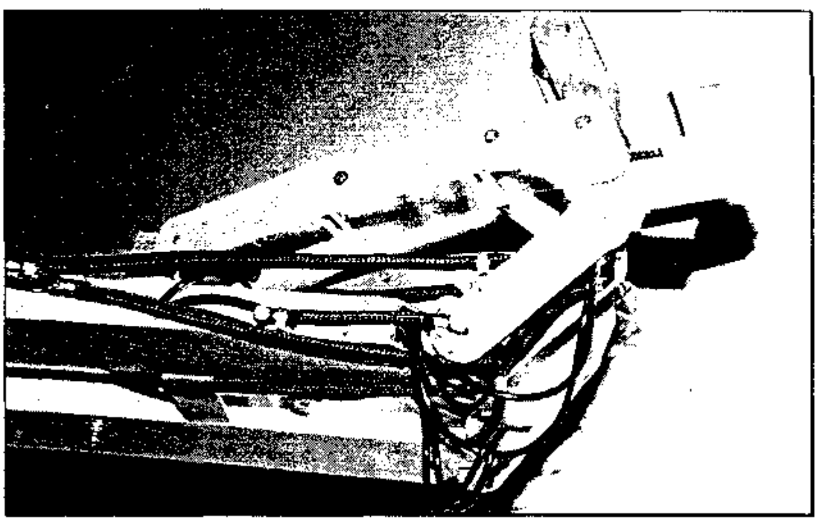

Figure 4-11: PTIRH's version of the lateral grasp.

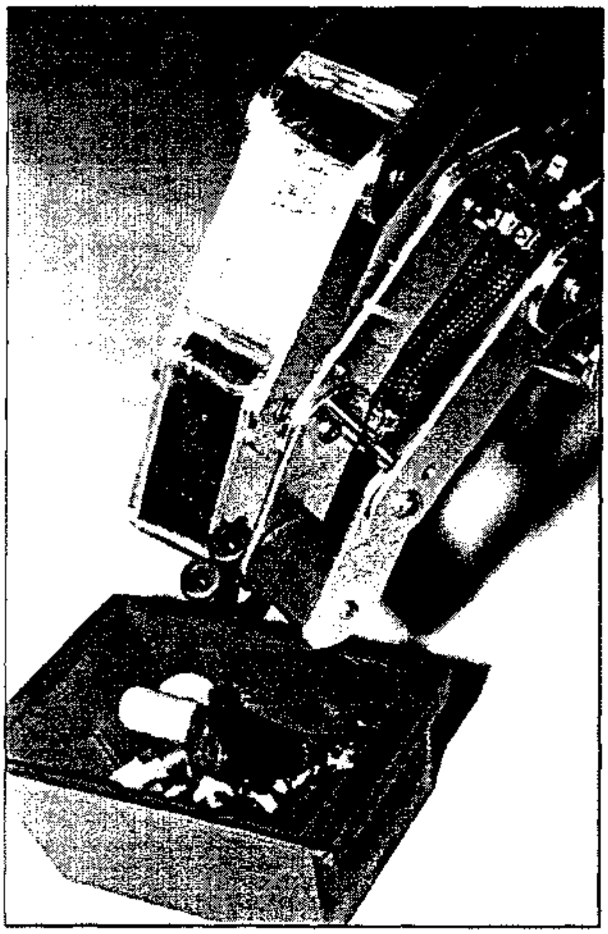

Figure 4-12: The tweezers grasp.

Section 2.3.2 described manipulations considered necessary for a multi-fingered robot hand to be useful in the factory or laboratory. The remainder of this section describes how these manipulations could be improved by having two thumbs.

The trigger manipulation could be improved by having two thumbs as the tool could have a larger number of triggers to push. Each thumb would also be able to manipulate triggers while the other thumb and fingers were holding the tool in a secure grasp.

In the transfer object manipulation where an object grasped between thumb and forefinger is drawn into a palm grip, two thumbs would be of assistance. The object could be held between the two thumb-finger pairs and drawn back, reducing any twisting effect and therefore having greater control.

The cutter's manipulation could be improved, as one thumb could be used to ensure that cutters do not fall out of the grip when the cutter is open.

The pen screw manipulation could be more easily controlled by rolling the pen down two thumbs, therefore having two points of contact.

The pen transfer, where a pen is picked up in the fingertips and then pushed round by the fingers to a writing position, may be improved by using the other thumb to do the pushing around.

In conclusion, an extra thumb therefore seems to offer an advantage in grasping and manipulations. The addition of an extra thumb will increase the complexity of the hand. If the advantage gained by having an extra thumb is greater than the extra complexity introduced then the concept is worthwhile.

4.6.4 Weight Considerations

The weight of the prototype modular finger is 320 grams. The weight of the early prototype hand, including the prototype finger, is 2.25 kilograms. The weight of the wrist was projected to be 1.2 kilograms. Therefore the hand has a maximum payload of 2.5 kilograms to stay within the limit of six kilograms imposed by the ASEA robot.

The weight of the robot hand can be reduced by removing unnecessary metal from the links, joints and palm. One of the attractions of the air muscles was their low weight, although they are relatively bulky.

The weight of the valves is considerable. At 300.3 grams each, the 32 valves needed for the four digits would weigh a total of 9.6 kilograms. Owing to the maximum payload of the robot arm, the valves would have to be located away from the air muscles on the forearm of the robot arm to avoid overloading it. Reengineering of the valves could be performed to reduce weight. Ideally the valves would be located on the hand, adjacent to the muscle they are supplying, in order to reduce time lag and minimise the effects of the fluid properties of air.

4.6.5 Number of Axes and Degrees-of-Freedom

The prototype finger has four degrees-of-freedom with two axes of movement. The thumb joints, as they ended up being constructed, have another axis of movement to give them roll, pitch and yaw. However, the yaw movement is not utilised in most of the grasps shown in section 4.6.3. The thumb joints are capable of circumduction.

4.6.6 Desire for Modularity

Apart from the joints at the base of the digits, the design is modular in nature. This modularity makes construction of the hand easier. The universal joint at the base of the fingers is different from that of the thumbs as a degree-of-freedom is added in a different axis.

4.6.7 Hand 'Intelligence' Considerations

The prototype finger is capable of intelligence if a suitable control system is implemented. The pressure sensors give feedback to the valve control system to enable pressure control of the muscles, which changes the joint angles. The potentiometers could be easily connected to this system also, as they provide position information about the joints, and may in fact give better feedback information to get the joints at the desired angles as they are independent of the air muscles system. The force sensors need to be integrated into a higher level control system. With an intelligent control system that has a database of hand manipulations and grasps and an expert system to decide when and how to use the grasps, a low level controller would have enough feedback information to control the trajectories of the digits. This would enable PTIRH to be intelligently controlled so as to attain the performance tasks of small assembly and large object manipulation.

4.6.8 Size Considerations

The size of PTIRH has been influenced by the use of the air muscles as actuators. Use of the smallest in the range of muscles provided by the Shadow Robot Company, means that the hand will be twice as large as a large human hand. This is only a disadvantage in that human tools may not be able to be used by PTIRH. Other applications will be able to be found.

To reduce the size of the hand, if this becomes necessary, it may be possible to get specially made smaller air muscles, or the air muscles may have to be abandoned in favour of smaller, conventional, pneumatic actuators or some other small actuator. These would have the disadvantages of cost and weight.

4.6.9 Performance Objectives

4.6.9.1 Speed

The air muscles inflate from fully deflated as quickly as the air pressure can be increased. With a 600 kiloPascals inlet pressure on the valve, as soon as the valve is turned on the muscle is inflated. The shock load of this quick inflation has caused several of the sample air muscles to pull apart at the crimp. The potential for a fast acting robot hand exists, however, the crimp on the muscles needs to be strengthened.

4.6.9.2 Reliability

The reliability of a robot hand is extremely important. Owing to the desire for universality, robot hands are extremely complicated mechanisms and will only be useful if their reliability is high. Design considerations such as redundant sensors, error checking of the sensors, calibration and initialisation issues, actuator reliability, mean time between failures testing and mechanical strength are important when considering the overall reliability of the robot hand.

4.6.9.3 Accuracy and Precision

The accuracy of a robot hand to perform operations and the precision with which it does this are also important considerations. The human hand can be trained to be accurate and precise by the brain. An intelligent control system should ensure that PTIRH will be consistently accurate and precise.

4.6.9.4 Resolution

The valves are the limiting factor in the resolution of PTIRH at this point. It is desirable that a resolution of at least one degree is achievable in order for PTIRH to achieve its overall objectives. With the mini air muscles having a volume of 5.24 cubic centimetres this means the valve has to be capable of bursts of air of only 0.0582 cubic centimetres in volume. This is a strenuous requirement and one the valve may not be capable of with a supply pressure of 600 kiloPascals. As the air muscle contracts the most between 100-400 kiloPascals it may be possible to run the valve at a maximum supply pressure of 400 kiloPascals and still achieve good results in other areas.

4.6.9.5 Work Envelope

The work envelope is the result of the range of movement that each joint has. Figure 4-13 shows the range of movement each joint has in response to the changes in pressure of the air muscles. Figure 4-14 shows the yaw response of Joint0.

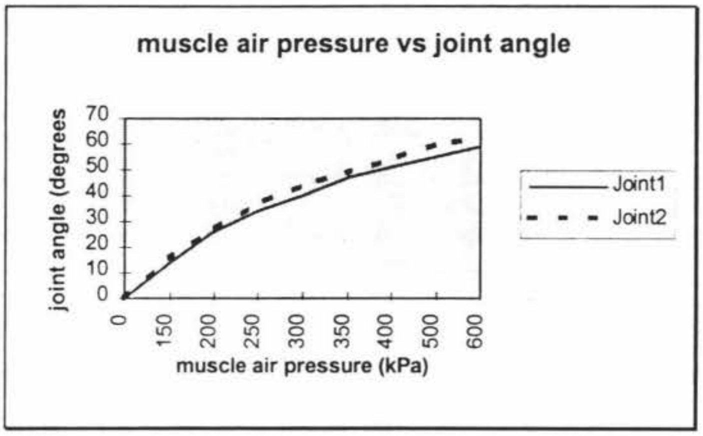

Figure 4-13: Joint responses to changes in muscle pressure.

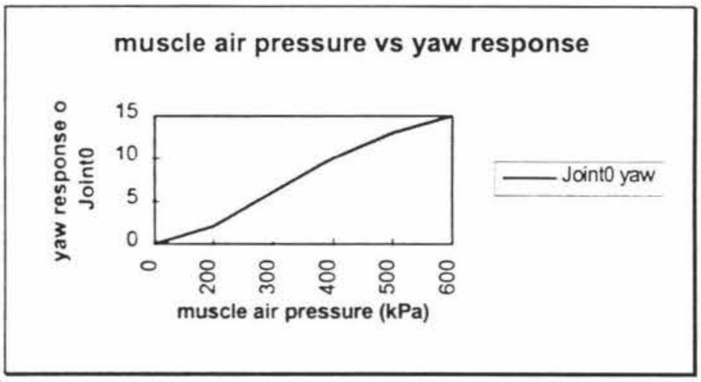

Figure 4-14: Yaw of Joint0

From these graphs it can be seen that the desired yaw of fifteen degrees for each of adduction and abduction was achieved, while it appears that the desired range of movement of 85 degrees for Joint1 and Joint2 was not achieved. In fact, the measurements are taken from the fully extended position, which is 25 degrees below the horizontal for Joint1, giving a total range of movement of 84 degrees. For Joint2, the fully extended position is ten degrees below the horizontal, giving a total range of movement of 72 degrees. The fully extended position is where the extending muscle is fully inflated and the retracting muscle is fully deflated. As the retracting muscle is inflated, the extending muscle is deflated, until at full retraction the opposite occurs.

Joint0 has a range of movement of 108 degrees, so this gives a large work envelope, more than twice as large as a human forefinger, owing to the large size of the robot finger.

4.6.9.6 Dexterity and Usefulness

Dexterity will largely be the result of the sensors used and the intelligent control system developed to utilise the sensors. The mechanical design of the robot hand has resulted in fingers with no circumduction in the metacarpal-phalangeal joints. As this movement is important in the human hand, it remains to be seen how important it is in a robot hand.

The usefulness of PTIRH will largely be dependent on how dexterous it is.

4.6.9.7 Power of PTIRH

At 600 kiloPascals the force exerted at the fingertip of the prototype robotic finger is 1.30 kgf. With a maximum payload of 2.2 kilograms and three digits with actuation to be added, this force should be sufficient to carry out grasping and dexterous manipulation operations. Figure 4-15 shows how the force exerted rises with the increased air pressure of the retracting air muscles. As would be expected the finger develops the most force when all the retracting air muscles are fully inflated. If more force is desired more muscles could be added to the joints in parallel with the existing muscles or the finger design could be modified to increase the force exerted by the muscles at the expense of the range of movement of the joint.

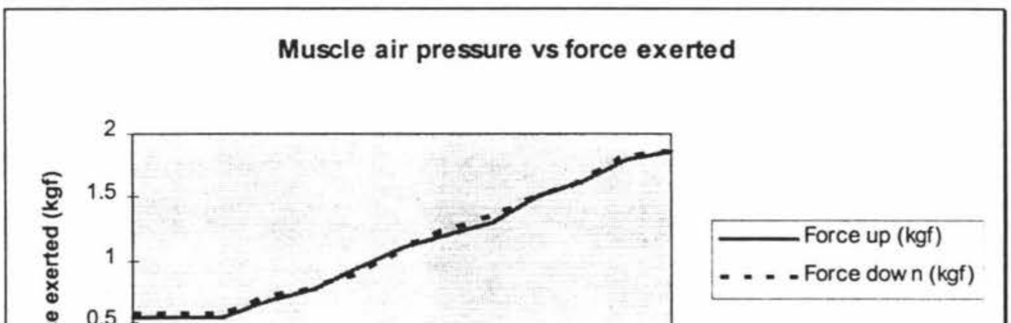

Figure 4-15: The force exerted at the fingertip

4.6.10 Compliance Considerations.

The air muscles are inherently compliant. It was decided to make this a desirable feature of the hand and control the compliance as much as possible. With both positional and torque information for a joint this will be possible with the implementation of a control system.

Testing showed that the compliance could be controlled but never fully removed, which could prove a problem. Both muscles of Joint2 were inflated to 600 kiloPascals and the joint was perturbed manually. This test showed that the joint position was not fixed, but could be altered as much as twenty degrees by external forces. It had been believed that the muscles would not be compliant when both were inflated to 600 kiloPascals, but the inherent compressibility of air proved to be a bigger factor than first thought. As could be expected, in Joint1, with muscles operating in pairs, the problem was not as great owing to the increase in force. External forces altered the joint position by fifteen degrees.

4.6.11 Cost considerations

The cost of the early prototype robot hand was $5,605. This figure includes materials and manufacturing time for the robot hand and also for the robot wrist that was designed and developed earlier. This figure is low for a robotic end effector and includes some research and development time that could be recouped through the commercialisation of some aspects of the project. A breakdown of the figure above is given in Appendix D.

4.7 Conclusions

Evaluation of the sub-sections that make up the overall PTIRH project has been continuously occurring in a cyclical fashion. The design of the robot hand proceeded in an empirical fashion, with alterations being made after evaluation of the work to date and these alterations fed back into the design process to be evaluated in their turn.

Evaluation of the valve was initially promising and so the decision was made to continue with the air muscles. As time continued the problems with the valve were not able to be overcome and this impacted heavily upon the success of the air muscles as actuators for PTIRH and the prototype robotic finger. Evaluation of the valve has suggested a redesign of the mechanism so as to achieve quicker open/close cycles and to let a maximum of 50 cubic millimetres through with each burst. The possibility of reducing the air supply pressure has also been raised. This latter approach would have an impact on the maximum force that could be achieved but it may be worthwhile to trade off strength against dexterity. This is a common problem with robot hands [28]. Other tradeoffs often made are between sensitivity and speed, and accuracy and range of movement.

The sensors that are currently operational on the prototype robotic finger work well and will form the basis of the feedback to an intelligent controller that will be able to react to external situations depending on the information gained from the sensors. More tactile and force sensing sensors should be added to provide tactile information over the whole grasping surface of the robot hand, which includes the palm and possibly the outside of the fingers.

The air muscles have many advantages over conventional actuators in the robot hand application. It remains to be seen how they will perform in the long term and in harsh industrial environments. The major problem with air muscles is the necessity to supply them with air. This means long air lines and problems associated with the compressibility of air and its fluid characteristics. If the valves could be situated close to the air muscles then this would not be so much of a problem, but at 300.3 grams each the valves are much too heavy to do this.

The validity of the concept of a multi-fingered gripper with two thumbs and two fingers has been proven. By analysing the grasps such a robot hand could perform, and using an early prototype of such a hand to demonstrate that such grasps can be performed, it has been shown that the concept is sound.

The development of an intelligent control system is to begin in the future. When this occurs, the development of PTIRH from an early prototype, which has been shown to have the capability to become intelligent, to a true intelligent robot hand could become reality.

4.8 References

[1] Spellman, A.M.E., *A Servo Pneumatic Valve to Control Air Muscles*, Final Year Project, Department of Production Technology, Massey University, New Zealand, 1995.

[2] Yee, N., *Mathematical Modelling and Control of a Robotic Manipulator*, MTech Thesis, Massey University, December, 1996.

Chapter 5

CONCLUSIONS

Robotic systems are becoming more universal in application. Ideally a single end effector would be able to perform every operation required of the robot system. Instead of being just a complicated tool on the end of the robot arm, the end effector should be capable of using other tools. Universal robot hands are becoming essential for applications in which changes in robot arm end effectors are undesirable and high flexibility of operation is important. Space exploration is one field where it is desirable that a single end effector can grasp and manipulate any object necessary. In the factory, time spent changing end effectors can delay an automated process and a single multi purpose gripper can be cheaper than several dedicated grippers.

Present universal end effector designs fall into two areas: those of an anthropomorphic configuration and those which are multi-fingered manipulators which do not resemble the human hand. Both of these configurations are known under the generic term of robot hands.

Production Technology's Intelligent Robot Hand (PTIRH) project is a multi-fingered manipulator of non-anthropomorphic configuration. PTIRH will have an intelligent control system in order to have high flexibility of operation, approaching the flexibility required of a universal robotic end effector. PTIRH has a configuration of two thumbs and two fingers, and position, force and air pressure sensors are installed to provide feedback to the soon to be developed intelligent controller. PTIRH is capable of all six generic grasps and the two thumbs mean that the grasps will be stable.

This thesis has been concerned with the author's work on the background research into the state of the art in robot hands; investigation, analysis and demonstration of possible grasps with two thumbs; investigation and choice of a suitable actuator and sensors; the design, development, construction and modification of a control valve to use with the actuator; the specification of the prototype robot hand; the construction of an early prototype hand with one actuated finger and three digits without actuation; the testing of the hand; and the evaluation and discussion of the testing results. Development of an intelligent control system falls outside the scope of the author's research and will be undertaken by other post graduate students in the department. However, some possibilities for the future work on the design of an intelligent control system are considered in section 6.2.

The prototype robot hand had been shown to have the components necessary for an intelligent robot hand, however, without an intelligent controller, it is impossible to show that PTIRH is, in fact, an intelligent robot hand. The prototype hand has two concepts underpinning its design which should reduce the complexity of the intelligent controller.

First, PTIRH is a multi-fingered manipulator of a symmetrical configuration that will enable PTIRH to have less reliance on friction in grasping and manipulation of objects. The author has shown that a robot hand with two thumbs and two fingers will be more successful in grasping in an industrial situation than robot hands of an anthropomorphic configuration. PTIRH can perform grasps and manipulations not possible for a robot hand with only one thumb.

Second, PTIRH uses air muscle actuators and these possess characteristics which will minimise the complexity of the control system. The air muscles have inherent compliance due to the pneumatic principles underlying their operation and finger and thumb joints can have their compliance actively controlled with the pressure, position and force sensing feedback. The air muscles directly actuate the joints, which will avoid problems that appear in other robot hands which are remotely actuated using artificial tendons. However, a disadvantage with the air muscles is that they need a pneumatic control valve, with air lines between the valve and the air muscles. If these air lines become lengthy, there are problems with hysteresis and time lag, hence the complexity of the controller could increase. Locating the control valves on the robot forearm would mean that the air lines could be up to 800 millimetres long. No testing has been performed to ascertain the extent to which this could be a problem.

The control valves have been a problem and have held up the project. Design and development of a servo pneumatic valve has continued parallel with the design and development of the early prototype robot hand, but when the hand was ready to implement the valves, the valves had not been developed to a point where they could be used. The valves were being operated at a supply pressure of 600 kiloPascals and needed to supply a maximum of fifty cubic millimetres in one pulse, but could only deliver a minimum of 500 cubic millimeters or one tenth of the volume of the mini air muscle. The author was involved with the valve project from the conception, the design, through to the construction, testing, modifications and further testing.

Testing of the valves showed that the concept worked but the valves needed further refinement to be applied to the mini air muscles. Testing of the switching frequency of the valves gave a result of 100 Hertz, which is fast enough for the control of the valves once the problems with the volume of air being switched is overcome.

Pressure sensors were developed to supply feedback to the valves and these worked very well. Two types were developed: strain gauge based and capacitive based. Evaluation of the sensors by the author resulted in the capacitive sensor being chosen for evaluation due to its low cost, simplicity and lack of need for amplification.

The early prototype of PTIRH that was developed has a number of strengths and limitations. The main strength is the flexibility that the multi-fingered configuration of two thumbs and two fingers provides for a robot hand in an industrial situation. The main limitation of the system is that the actuators chosen, which were being used in a novel fashion as robot hand actuators, are of a small volume and the servo pneumatic valve developed to control the mini-muscles lets too large a volume of air through with each pulse.

The PTIRH project has proceeded to a stage where the concept has been validated and partially implemented. Future work now needs to be carried out to fully implement PTIRH.

Chapter 6

FUTURE WORK

6.1 Introduction

There is much work to be carried out in the future for PTIRH to become fully operational. Other robot hands have been in development for at least 30 years, in the case of the Belgrade/USC hand or ten years in the case of the UMDH and the Salisbury hand. However, an early prototype of the mechanical hand has been constructed and this will provide the basis for work on the intelligent control of PTIRH.

This chapter discusses the three main areas of future work considered to be the most important to the development of PTIRH. Section two discusses control strategies, section three discusses the air muscles and section four outlines work to be carried out on the valves. Section five concludes the chapter.

6.2 Control of PTIRH

The control of PTIRH can be broken down into two main areas. Firstly, there is the control of the individual digits' movements. This involves processing the sensor feedback and outputting signals to move the digits from the present location to the desired location. Secondly, there is the overall control of the movement of the hand. This is the grasping and manipulation database for how the hand moves - the decisions on what the desired location of the individual digits should be. Essentially, there needs to be a low level controller for calculating the joint torques and trajectories and a high level controller for deciding what the desired joint torque and strategies should be.

The control is complicated by a number of factors: the large number of degrees-of-freedom that must be coordinated to provide the desired hand movement; the management of the valves to drive the air muscles and the feedback from the valves; the integration of the joint position information and force sensors; and the calibration of the various sub-systems of the hand.

The control of PTIRH was given to a Masters student who elected to attempt to develop a model based controller [1]. A model was developed for the air muscles and progress was made in implementing a control program for a single muscle and valve. The development of a high level controller is to be another project altogether.

In robotics the kinematic problem of knowing the joint positions and from these calculating the position of the end effector (the fingertip in the case of PTIRH) has a corollary: knowing the desired position of the end effector, what joint angles are necessary to achieve this position? This is known as inverse kinematics and is a computationally intense process. As well as calculating the inverse kinematic equations, control values are needed to eliminate overshoot while achieving fast movement.

Many industrial robots ignore coupling effects between joints and use a simple PD control strategy, where the position of the joint is used as feedback. Industrial robots often use only simple trajectories and so have no problem. When more complex trajectories are needed, the speed of the robot can drop dramatically and positional errors can begin to occur. Control systems for robot hands using these traditional control strategies are complicated by the necessity to coordinate the movement of the fingers in a confined workspace. However, many of the current robot hands use some form of traditional kinematic and dynamic equations to control the links that make up the hands. The UMDH has had a modal state position controller developed [2]. Kang and Ikeuchi [3] suggest a control system involving demonstrating a grasping task to the UMDH via *Cyber*Glove. The system then breaks down the grasping task as observed into action segments such as approach object, grasp object, manipulate object, place object and depart. The robot hand can then replicate the grasping task. The Salisbury hand has had an object stiffness control system implemented [4]. Research has been carried out on kinematic and force analysis of robot hands for many years [5, 6, 7, 8, 9] and is still continuing [10, 11, 12, 13, 14].

In order to develop an intelligent control system for PTIRH, less traditional control strategies need to be explored. An obvious starting point is to explore how the human hand is controlled. The complex parallel processing neural network of the human brain is the subject of imitation attempts, but none have been totally successful. However, neural computing is the subject of much research [15, 16, 17, 18, 19]. Fuzzy logic is also the focus of research and has been applied to robot hand control [20]. Other areas of intelligent control are being explored [21].

The range and number of grasps and manipulations that human hands have is extremely broad and extensive. The redundant skeletal degrees-of-freedom, the large number of muscles available to move the joints, and the control provided by the brain and nervous system enable a great many alternative grasping strategies. In view of the large number of alternative strategies, it has been suggested that human grasping is drawn from heuristic criteria based on experience [22]. Heuristic approaches help problem solving by limiting the search for solutions in the problem space, without necessarily taking into account the whole problem domain.

The need for real time control of a intelligent robotic hand means that the computationally intense, and hence slow, approach of solving inverse kinematic and dynamic equations is not suitable. Instead, Bekey et al. [22] suggest that given knowledge about the robot hand, the target object geometry, the task to be performed and human grasping, an appropriate grasp posture can be selected. The Belgrade/USC hand was used to implement the grasp planner developed. The design of this hand meant that finger coordination and shape adaptation is performed automatically, thus the grasp planner would be more difficult to implement on other robot hands.

Future work on the control of PTIRH should initially focus on the low level control of a whole finger in order to enable it to reach desired positions. As each joint is independently actuated, the mechanism is uncoupled. It is possible that a simple PD controller could be implemented at the low level. A higher level control will then need to be implemented, including a knowledge base of grasps and manipulations, to give the desired positions to the low level controller. The knowledge base could be derived from a grasp planner similar to that outlined in the previous paragraph.

6.3 Decreasing the Size of the Air Muscles

At present the prototype intelligent robotic finger that will make up the digits of PTIRH is twice the size of a large human finger. This is due to the actuators, the air muscles. Despite being the mini version of the standard air muscle, they are still too long for use in a human sized hand. The Shadow Robot Project process the materials in their air muscle in some fashion in order to achieve better performance. They would probably be interested in building a smaller muscle for our use, but this would come at a price.

The principle behind the air muscle's construction is simple enough and is the basis of other similar actuators, and Steve Schaare, Mechatronics Technician, has spent some time experimenting with different materials in order to develop a functionally similar, but smaller, pneumatic actuator.

The alternative to buying or developing a smaller air muscle is to use a different type of actuator, which will be able to achieve the desired hand size. This would mean repeating the design process entirely.

6.4 Refinement of the Servo Pneumatic Valve

The servo pneumatic valve controlling the pressure of the air muscles has proved a constraint to the implementation of PTIRH. It is possible that by operating the air muscles and valve at 600 kiloPascals that they are at the limits of their capabilities. Exploring the results of reducing the maximum operating pressure of the valve and air muscles should precede any further refinements to the valve. It should be noted that it is the small volume of the air muscles which is causing problems. If work is done in reducing the size and volume of the air muscles as suggested in the previous section, then the problems caused by the valve will be made worse.

The valve can be refined in two ways to reduce the volume of air being sent to the air muscles, besides reducing the air supply pressure as already mentioned. First, the aperture of the inlet valve could be reduced. This has already been reduced to 0.5 millimetres from two millimetres, without the desired result. Second, the length of time the inlet valve is open could be reduced. This would involve changes to the coil and driver circuit.

6.5 Conclusions

Much work has been carried out on PTIRH and there are three main areas of future work to be considered: control, air muscles actuation and the valves for the air muscles. The control and the valves are the most important, with a change in the actuation being used resulting in the design process needing to be repeated. Work on the valves should be carried out first, while the control work could proceed in parallel to some extent.

This future work on PTIRH will be an exciting stage of the project and should result in PTIRH becoming a functional robot hand.

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Appendix A

AIR MUSCLE DATA

Table 1: Output of the capacitive pressure sensor:

Air Pressure	Output up(V)	Output down(V)
0	2.736	2.736
50	2.762	2.754
100	2.795	2.804
150	2.842	2.84
200	2.891	2.88
250	2.944	2.94
300	3.004	2.99
350	3.064	3.06
400	3.144	3.13
450	3.227	3.22
500	3.32	3.32
550	3.46	3.48

Table 2: Output of the Strain gauge pressure sensor:

Air Pressure	Output up (V)	Output down (V)
0	2.942	2.942
50	3.131	3.184
100	3.48	3.515
150	3.872	3.905
200	4.188	4.288
250	4.551	4.626
300	4.91	5.021
350	5.292	5.366
400	5.616	5.73
450	5.97	6.14
500	6.341	6.515
550	6.993	6.863

Table 3: Output of the Joint1 potentiometer:

Air Pressure	Joint1 up	Joint1 down
0	686	672
50	686	672
100	686	672
150	686	648
200	624	590
250	578	550
300	546	516
350	520	490
400	498	470
450	482	452
500	468	444
550	452	442
600	442	442

Table 4: Output of the joint2 potentiometer

Air Pressure	Joint2 up
0	668
50	668
100	668
150	668
200	668
250	660
300	654
350	644
400	634
450	624
500	612
550	600
600	592
650	582

Table 5: Change in joint angles for Joint1 and Joint2 pitch in response to step changes in input air pressure:

Air Pressure	Joint1	Joint2
0	0	0
150	14	16
200	26	27
250	34	37
300	40	44
350	47	49
400	51	54
500	55	60
600	59	62

Table 6: Change in yaw angle for Joint1 in response to step changes in the input air pressure:

Air Pressure	Joint0 yaw
0	0
200	2
300	6
400	10
500	13
600	15

Table 7: Force exerted at the fingertip by inflating all of the retracting air muscles in response to step changes in the input air pressure:

Air pressure (kPa)	Force up (kgf)	Force down (kgf)
0	0.55	0.57
50	0.55	0.57
100	0.55	0.57
150	0.67	0.7
200	0.77	0.79
250	0.95	0.9
300	1.11	1.1
350	1.2	1.25
400	1.3	1.35
450	1.5	1.5
500	1.61	1.62
550	1.8	1.82
600	1.85	1.85

Table 8 Stroke of mini muscles for a load of 500g

Muscle No.	Deflated	Inflated	Stroke
1	95	78	17
2	95	78	17
3	94	77	17
4	98	80	18
5	77	59	18
6	78	60	18

Table 9: Stroke of bigfoot muscles for a load of 1kg

Muscle No.	Deflated	Inflated	Stroke
1	264	191	73
2	228	175	53
3	254	185	69
4	260	190	70
5	261	190	71
6	253	195	58
7	245	182	63
8	228	176	52
9	253	185	68
10	254	185	69
11	258	189	69

Table 10: Mini air muscles lengths at different pressures and loads

Pressure	1004.7g load	1705.3g load	2003.36 g load
0	72.33	73.7	73.78
50	71.82	73.36	72.84
100	70.68	72.74	72.14
150	67.72	70.43	71.5
200	64.12	67.98	68.23
250	61.32	64.42	65.77
300	58.83	62.3	62.78
350	56.84	60.32	60.78
400	55.86	59.02	58.99
450	55.13	57.85	57.6
500	54.31	56.43	56.9
550	53.78	56.26	56.78
600	53.24	55.32	55.14

Table 11: Mini air muscles diameters at different pressures and loads

Pressure	1004.7g load	1705.3g load	2003.36g load
0	6.06	6.23	6.32
50	6.38	6.23	6.48
100	6.96	6.61	6.66
150	7.91	7.27	7.15
200	9.32	8.35	8.04
250	9.12	9.18	8.82
300	10.19	9.77	9.55
350	10.66	10.15	9.98
400	10.82	10.5	10.27
450	10.96	10.68	10.54
500	11.06	10.86	10.72
550	11.19	10.88	10.85
600	11.25	10.98	10.95

Table 12: Mini air muscles diameters at different pressures and loads

Pressure	1004.7g load	1705.3g load	2003.36g load
0	2089.07	2249.74	2317.72
50	2299.19	2239.36	2405.52
100	2692.80	2499.57	2516.59
150	3332.41	2927.62	2874.79
200	4380.40	3727.71	3468.77
250	4011.26	4269.67	4023.96
300	4804.36	4676.98	4503.15
350	5079.92	4887.45	4761.13
400	5143.33	5117.60	4893.37
450	5208.32	5189.61	5032.60
500	5224.91	5234.30	5142.69
550	5296.26	5237.77	5257.07
600	5299.46	5245.36	5199.76

Appendix B

HAND DRAWINGS

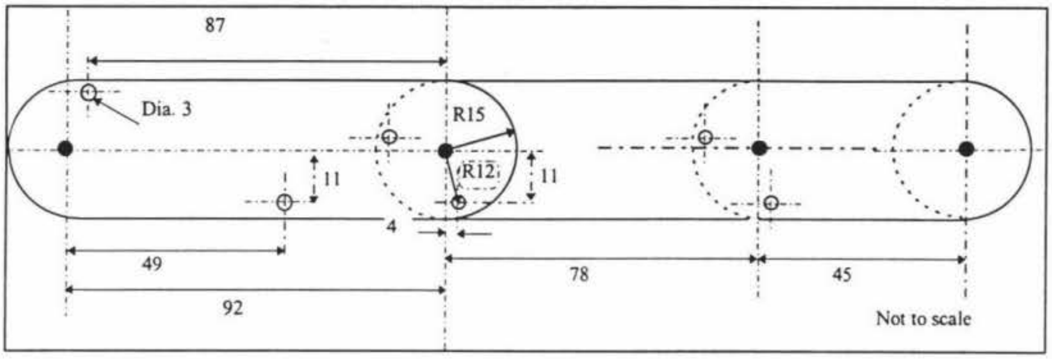

Figure 1: Side view of finger.

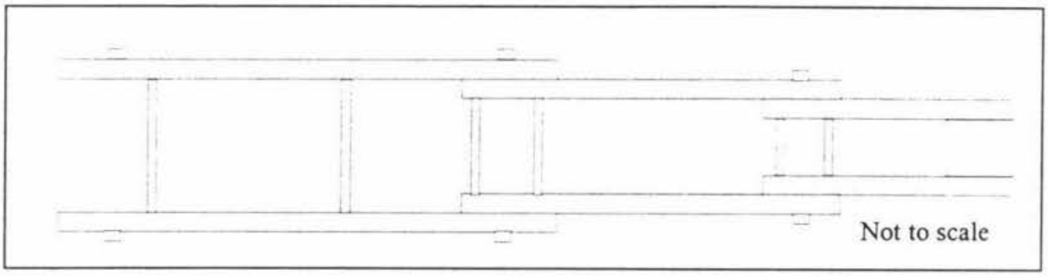

Figure 2: Top view of the finger showing the nested link arrangement.

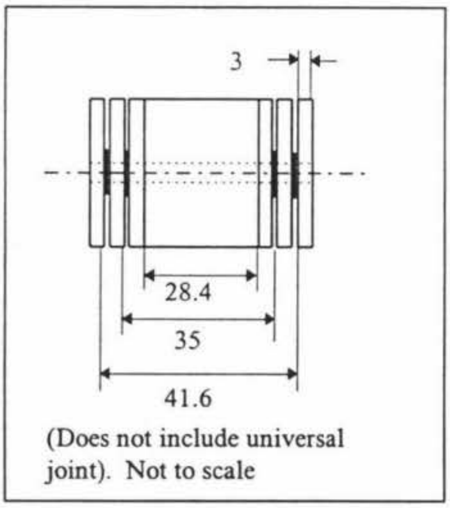

Figure 3: Proximal end view of finger

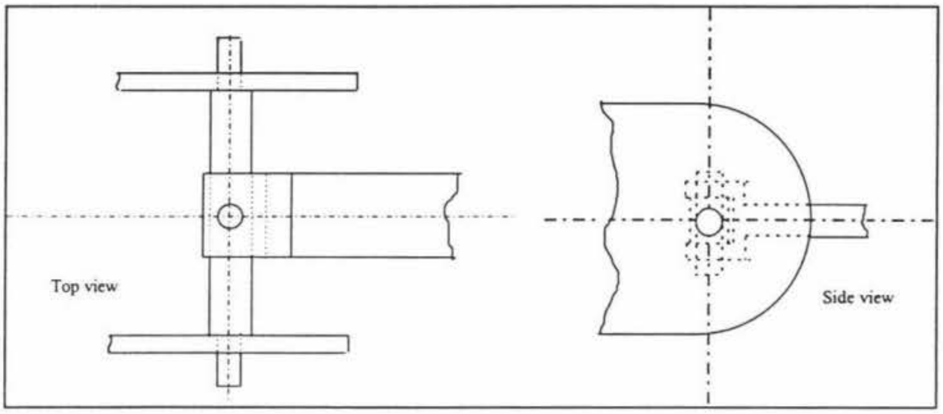

Figure 4: Universal joint detail.

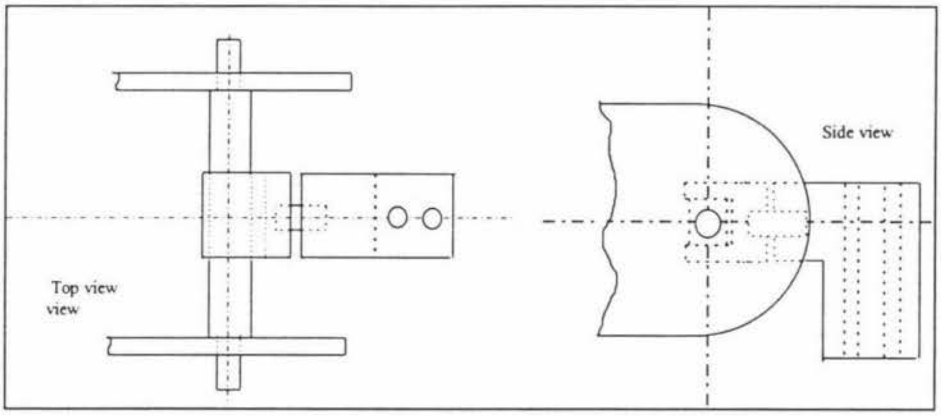

Figure 5: Thumb joint detail.

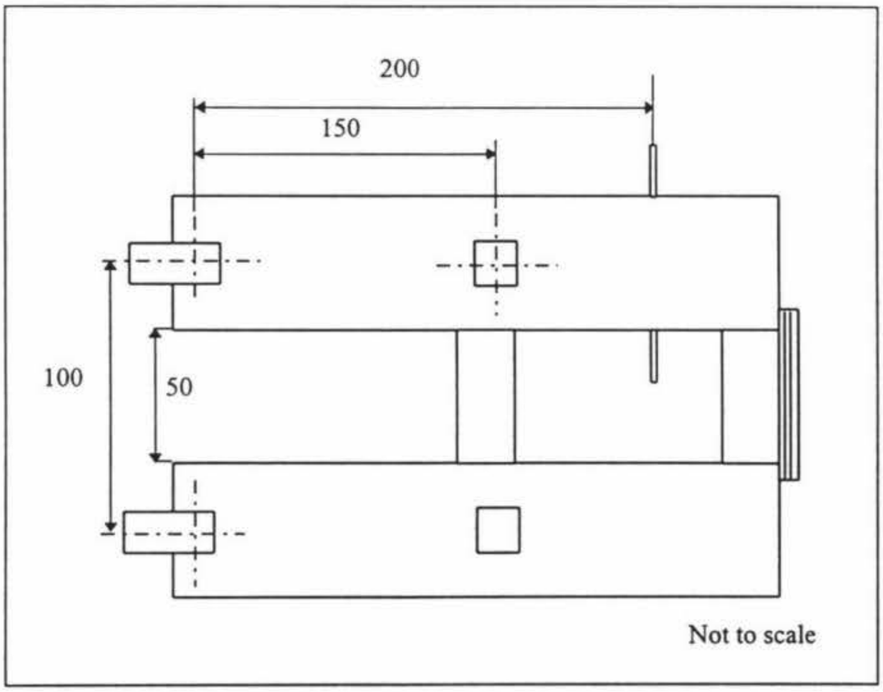

Figure 6: Top view of the palm.

Appendix C

PROGRAM LISTINGS

1. Potentiometer Output Program for Joint1 and Joint2

```
{$C- PROGRAM BY MATT HARRIS TO READ JOINT ANGLE SENSORS
      OF ROBOT FINGER.  VERSION 0.1a}

PROGRAM  JOINT_ANGLE_READING;

VAR
      difference, a : INTEGER;
      detect : BOOLEAN;
      x, y, l, m, joint_one, joint_two : WORD;


PROCEDURE Read_Joint_One;
      BEGIN
            ADCON := $06;                          {clears the ADC register}
            ADCON := ADCON OR $08;                 {starts ADC on port 0}
            WHILE NOT ((ADCON AND $10)=$10) DO;{waits until
                                                conversion is completed}
            x := ADCH;                             {gets the higher bit}
            y := ADCON;                            {gets lower 2 bits}
            joint_one := ((x*$04)+(y DIV $20));    {computes into 10 bit form}
            WRITELN(joint_one);                    {writes output of joint one
            ADCON := ADCON AND $EF;                {clears A/D register}
      END;


PROCEDURE Read_Joint_Two;
      BEGIN
            ADCON := $04;
            ADCON := ADCON or $08;
            WHILE NOT ((ADCON AND $10) = $10) DO;
            l := ADCH;
            m := ADCON;
            joint_two := ((l*$04)+(m DIV $20));
            WRITELN (' ',joint_two);
            ADCON := ADCON AND $EF;
      end;


PROCEDURE Wait;

VAR i:INTEGER;
```

```
BEGIN
        REPEAT
                INC(i)
        UNTIL (i=10000);
END;

{Main Program}

BEGIN

        RESET(serial);
        WRITELN;
        REPEAT
                Read_Joint_One;
                Read_Joint_Two;
                Wait;
        UNTIL FALSE;

END.
```

2. Bang-Bang Single Valve Control Program

```
{$C- valve program "mattv1". }

{$M $0000 -1}

PROGRAM single_valve_controller;

VAR
        difference:INTEGER;
        actual_strain,x,y,l,m,desired_strain:WORD;


PROCEDURE Wait(time:byte); {procedure to put a delay into program}

VAR
        i:INTEGER;
        length:BYTE;

BEGIN
        {writeln('got to wait');}
        length:=0;
        i:=0;
        REPEAT
                BEGIN
                REPEAT
                        i:=i+1;
                UNTIL i=6;
                length:=length + 1;
                END;
        UNTIL (length = time);
END;


PROCEDURE Start_ADC_for_transducer;  {procedure to read the pressure transducer}

BEGIN
        x:=0;
        y:=0;
        ADCON:=$06;                              {clears the ADC register}
        ADCON:=ADCON OR $08;                     {starts ADC on port 0}
        REPEAT UNTIL ((ADCON AND $10)=$10);      {waits until conversion is
                                                  completed}
        x:=ADCH;                                 {gets the higher bit}
        y:=ADCON;                         {gets lower 2 bits}
```

```
        actual_strain := ((x*$04)+(y DIV $20));        {computes into 10 bit form}
        WRITE('a ',actual_strain);
        ADCON := ADCON AND $EF;
        {wait(2);}
END;

PROCEDURE Start_ADC_for_potentiometer; {procedure to read desired strain from
                                        potentiometer}

BEGIN
        l:=0;
        m:=0;
        {writeln('pot ad');}
        ADCON:=$03;
        ADCON:=ADCON OR $08;
        REPEAT UNTIL ((ADCON AND $10)=$10);
        {writeln('end pot ad');}
        l:=ADCH;
        m:=ADCON;
        desired_strain:=((l*$04)+(m DIV $20));
        writeln(' d ',desired_strain);
        ADCON:=ADCON AND $EF;
        {wait(2);}
END;


PROCEDURE compare_actual_with_desired; {self explanatory}

BEGIN
        {writeln('compare');}
        difference := desired_strain - (actual_strain);
        WRITELN;
        WRITELN('     diff is ',difference);
        {wait(2);}
END;


PROCEDURE operate_valve; {turns the inlet and outlet on and off in response to the
                         difference between the actual and desired pressures}

BEGIN
        p1.1:=true; {next 5 lines initialise valves and leds}
        p1.5:=true;
        p1.0:=true;
        p1.2:=true;
        p1.4:=true;
        {writeln('got to operate valve');}
        IF ((difference>=15)AND(difference<=15)) THEN
```

```
            BEGIN
            p1.5:=false;                    {indicate no further operation required
                                            through red LED}
            WRITELN('at desired');
            END
        ELSE
            IF (difference > 15) THEN    {turn on inlet valve }
                BEGIN
                    p1.2:=false;     {turn on LED}
                    p1.0:=false;     {Turn on inlet valve}
                END
            ELSE
                IF (difference < 15) THEN    {turn on outlet valve }
                    BEGIN
                    p1.2:=false;             {turn on LED}
                    p1.4:=false;             {Turn on outlet valve}
                    END;
            END;
        END;


BEGIN {Main Program}
        reset(serial);
        WRITELN;
        WRITELN('start');
        REPEAT
            BEGIN
            Start_ADC_for_transducer;
            Start_ADC_for_potentiometer;
            compare_actual_with_desired;
            operate_valve;
            END;
        UNTIL false;
        p1.2:=false;
        p1.5:=false;
        p1.4:=false;
END.  {Main program}
```

3. Modified Single Valve Control Program

```
{$C- valve program "mattv2". Version 2.0 written by Matt Harris. Modified to open
valves for different time periods depending on how far the actual pressure was from the
set point}

{$M $0000 -1}

PROGRAM single_valve_controller;

VAR
        difference:INTEGER;
        actual_strain,x,y,l,m,desired_strain:WORD;


PROCEDURE Wait(time:byte); {procedure to put a delay into program}

VAR
        i:INTEGER;
        length:BYTE;

BEGIN
        {writeln('got to wait');}
        length:=0;
        i:=0;
        REPEAT
                BEGIN
                REPEAT
                        i:=i+1;
                UNTIL i=6;
                length:=length + 1;
                END;
        UNTIL (length = time);
END;


PROCEDURE Start_ADC_for_transducer;  {procedure to read the pressure transducer}

BEGIN
        x:=0;
        y:=0;
        ADCON:=$06;                              {clears the ADC register}
        ADCON:=ADCON OR $08;                     {starts ADC on port 0}
        REPEAT UNTIL ((ADCON AND $10)=$10);      {waits until conversion is
                                                  completed}
```

```
        x:=ADCH;                                {gets the higher bit}
        y:=ADCON;                          {gets lower 2 bits}
        actual_strain := ((x*$04)+(y DIV $20));     {computes into 10 bit form}
        WRITE('a ',actual_strain);
        ADCON := ADCON AND $EF;
        {wait(2);}
END;

PROCEDURE Start_ADC_for_potentiometer; {procedure to read desired strain from
                                                potentiometer}

BEGIN
        l:=0;
        m:=0;
        {writeln('pot ad');}
        ADCON:=$03;
        ADCON:=ADCON OR $08;
        REPEAT UNTIL ((ADCON AND $10)=$10);
        {writeln('end pot ad');}
        l:=ADCH;
        m:=ADCON;
        desired_strain:=((l*$04)+(m DIV $20));
        writeln(' d ',desired_strain);
        ADCON:=ADCON AND $EF;
        {wait(2);}
END;


PROCEDURE compare_actual_with_desired; {self explanatory}

BEGIN
        {writeln('compare');}
        difference := desired_strain - (actual_strain);
        WRITELN;
        WRITELN('      diff is ',difference);
        {wait(2);}
END;


PROCEDURE operate_valve_1; {turns the inlet and outlet on and off in response to the
                            difference between the actual and desired pressures}

BEGIN
        p1.1:=true; {next 5 lines initialise valves and leds}
        p1.5:=true;
        p1.0:=true;
        p1.2:=true;
        p1.4:=true;
```

```
        {writeln('got to operate valve');}
        IF ((difference <= 5) AND (difference >= -5)) THEN
        BEGIN
         p1.5:=false;                {indicate no further operation required
                                     through red LED}
         WRITELN('at desired');
        END

        ELSE
        IF (difference > 6) THEN      {when difference is small, turn valve on for short
                                     time}
        BEGIN
               WRITELN('    small in');
               p1.2:=false;                    {turn on LED}
               p1.0:=false;                    {Turn on inlet valve}
               wait(1);
               {p1.2:=true;}
               p1.0:=true;
        END

        ELSE
        IF (difference < -6) THEN     {when difference is small, turn valve on for short
                                     time}
        BEGIN
               WRITELN('    small out');
               p1.1:=false;                          {turn on out valve}
               p1.4:=false;                          {TURN ON led}
               wait(1);
               {p1.2:=true;}
               p1.1:=true;
        END
end;


PROCEDURE operate_valve; {turns the inlet and outlet on and off in response to the
                         difference between the actual and desired pressures}

BEGIN

        p1.1:=true; {next 5 lines initialise valves and leds}
        p1.5:=true;
        p1.0:=true;
        p1.2:=true;
        p1.4:=true;
        {writeln('got to operate valve');}

        IF ((difference <= 5) AND (difference >= -5)) THEN
        BEGIN
```

```
        p1.5:=false;                    {indicate no further operation required
                                        through red LED}
        WRITELN('at desired');
    END

    ELSE
    IF ((difference > 6) AND (difference <= 50)) THEN {when difference is small,
                                                  turn valve on for short time}
    BEGIN
        WRITELN('    small in');
        p1.2:=false;                                {turn on LED}
        p1.0:=false;                                {Turn on inlet valve}
        wait(2);
        {p1.2:=true;}
        p1.0:=true;
    END

    ELSE
    IF ((difference < -6) AND (difference >= -50)) THEN        {when difference is
small, turn valve on for short time}
    BEGIN
     WRITELN('   small out');
     p1.1:=false;                                   {turn on out valve}
     p1.4:=false;                               {TURN ON led}
     wait(2);
     {p1.2:=true;}
     p1.1:=true;
    END

    ELSE
    IF ((difference > 51) AND (difference < 100)) THEN        {when difference is
small, turn valve on for short time}
    BEGIN
        WRITELN('             medium in');
        p1.2:=false;                                {turn on LED}
        p1.0:=false;                                {Turn on inlet valve}
        wait(2);
        {p1.2:=true;}
        p1.0:=true;
    END

    ELSE
     IF ((difference < -51) AND (difference > -100)) THEN
        BEGIN
        WRITELN('             medium out');
        p1.1:=false;                        {turn on outlet valve}
        p1.4:=false;                        {turn on led}
        wait(2);
```

```
            p1.1:=true;
            {p1.4:=true;}
            END
        ELSE
            IF (difference > 101) THEN {when difference is large, turn valve on for
                                        longer}
            BEGIN
            WRITELN('                   large in');
            p1.2:=false;                {turn on led}
            p1.0:=false;                {turn on valve}
            wait(2);
            {p1.2:=true;}
            p1.0:=true;
            END
            ELSE
            IF (difference < -101) THEN
            BEGIN
                WRITELN('                       large out');
                p1.1:=false;            {turn on outlet valve}
                p1.4:=false;            {turn on led}
                wait(2);
                p1.1:=true;
                {p1.4:=true;}
                END

END;


BEGIN {Main Program}
    reset(serial);
    WRITELN;
    WRITELN('start');
    REPEAT
        BEGIN
        Start_ADC_for_transducer;
        Start_ADC_for_potentiometer;
        compare_actual_with_desired;
        operate_valve;
        {operate_valve_1;}
        writeln;
        writeln;
        writeln;
        END;
    UNTIL false;
    p1.2:=false;
    p1.5:=false;
    p1.4:=false;
END. {Main program}
```

Appendix D

COST BREAKDOWN OF THE PROTOTYPE ROBOT HAND

Cost of prototype:

One finger	valves and pressure sensors, materials and manufacture	$2000
	aluminium	$10
	screws, bushes	$5
	pneumatic fittings	$15
	air muscles	$102
	Interlink force sensor	$22
	potentiometers	$1
	manufacturing costs	$600
		$2755

Palm and wrist	Aluminium	$50
	screws	$5
	muscles	$160
	strain gauges	$40
	valves	$750
	Interlink force sensors	$25
	pneumatic fittings	$20
		$1050

Total costs for entire hand, with four actuated fingers: $12 070

Total costs for early prototype hand with one actuated finger: **$5 605**