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Hands: Human to Robotic

Sanjay Agrawal
University of Pennsylvania

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We discuss issues involved in the building of electro-mechanical manipulators and some of the mathematics used in analyzing the suitability of a design. We look at one of the earliest designs of a computer controlled articulated gripper, as well as two of the most prevalent designs in today's research world, the Stanford/JPL hand and the Utah/MIT had. Finally, we show why a more fundamental understanding of how human grasping works will help us design more useful manipulators.

Comments

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GRASP LAB 249

Sanjay Agrawal

University of Pennsylvania
School of Engineering and Applied Science
Computer and Information Science Department
Philadelphia, PA 19104-6389

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Abstract

Hands have for centuries been recognized as a fundamental tool for humans to gain an understanding of their environment and at the same time be able to manipulate it. In this presentation we will look at various studies made on the functionality and use of the human hand and examine the different approaches to analyzing and classifying human grasps and building a taxonomy of these grasps. We study the anatomy of the human hand, and examine experiments performed to understand the how gripping forces are applied when lifting objects, and the methods extraction of haptic information, by humans.

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Contents

1 Evolution

The hand clearly has multiple functions. We use the hand to grasp objects, to manipulate them, to learn about them and utilize them. Our very ability to manipulate our environs to best suit our needs is vastly dependent on our usage of our hands. Evolutionary theory places mans ability to make tools and use them as one of the factors that distinguishes humans from other primates.

The human ability to perform complex tasks using hands was till recently considered to be a function of our brain size and the development of our nervous system. It was believed that early humanoids had the same functional hand, but were not able to use it's dexterity. Again even though many of the higher primates are known to use tools, they were never thought to have made them. The discovery of the Olduvai hand, found buried along with some sophisticated tools, put some the previous theories of human hand development and usage into doubt.

The Olduvai hand had many of the same characteristics as the human hand. The thumb was able to oppose the digits, and even though the phalanges were slightly curved, the hand should have had no difficulty in building the tools found. It possessed much of the same ratios of metacarpels to phalanges that humans have, plus a wide fingertip to help in grasping tools.

Thus it is possible to hypothesize that the specialization of the hand evolved in parallel with the development of our neuromuscular abilities and brain. Other primates which evolved in parallel with the humanoids seem to have utilized their hands for different tasks, to which their hands adapted. For instance, many higher primates still have curved phalanges, to allow for better a hook grasp, as well as longer phalanges used to provide a combination hook and curl grasp.

2 The Human hand

The study of human hands, including its functionality, has been recorded as early as 200 A.D. by Galen in his treatise on human physiology and anatomy. Since then there have been numerous other works from the perspective of functional usage of the hand. Some of the more interesting ones include work by William Alcott M.D., in 1856, where he writes about the structure and use of the human hand and in the same period there was a book written by Charles Bell titled *The Hand, Its Mechanism and Vital Endowments as Envincing design.* These works focus more on trying to understand the different kinds of tasks humans commonly perform with their hand, and if their is a set of similar motions that are used. The study of the anatomy of the hand, as can be expected, was initiated by people in the medical profession, to allow them to understand the physiology and workings of hands. Some of the earlier, but well known hand surgeons have been: Ambrise Pare in the 16th century, Larrey, Duchene, Hughier and Dupuytren in the 19th century and Bunell and Kanavel in this century. These are but a few of the people who have contributed to our understanding of how hands function anatomically. The hand functions as articulately and flexibly as it does because of a number of complex subsystems that interact together. in the following sections we describe the anatomy and each individual subsystem in some detail, focusing more on the part each system plays in the working of the hand.

2.1 The Anatomy

The hand consists of 19 bones, 19 muscles and about 20 tendons, some of which are activated by the forearm muscles. The hand can be thought of as five rays, emanating from the point of the wrist, each ray comprising of the respective carpels, metacarpels and phalanges.

The basic architecture of the hand is based on the bones in the hand. The palm consists of the carpel and metacarpels. The carpels are arranged in an arc, with the capitate as the keystone, the trapezoid, and trapezium on the left and the hamate on the right. Two metacarpels, M2 and M3 are fixed to the trapezoid and capitate respectively. M1 is connected to the trapezium by a saddle joint. At this, the carpometacarpel joint of the thumb there are three possible motions: flexion/adduction or extension/abduction, adduction/abduction and Circumduction.

The Metacarpophalangeal joints are stable in flexion and mobile in extension. Due to the routing of the collateral ligaments these joints can perform both lateral as well as abduction-adduction motions when extended.

The Interphalangeal joints, the joints at the phalanges in the fingers, are stable in all positions, which is important while doing a pinch grasp, since it allows us to change the position of the gripped object within the grasp, while resisting any lateral motions.

The palm of the hand has two axes, of bending, the transverse axis and the longitudinal axis. In the former the four fingers bend inwards in such a manner that the more ulnar the fingers are, the more oblique the motion is inwards, towards the median axis. The longitudinal axis, which is only at an angle of 75 degrees from the transverse axis, has limited flexion, allowing the palm to form a cup like shape when the thumb is placed next to the index finger.

The wrist, if excluded from being a functional part of the hand though it plays a very important role in determining the flexion and extension of the digits. The wrist is often seen to reinforce the action done

Figure 11-1. Diagram of the extensor apparatus of the fingers (front and side views). 1 = interosseous muscle, 2 = extensor communis tendon, 3 = lumbrical muscle, 4 = tendon sheath, 5 = sagittal band, 6 = intermetacarpal ligament, 7 = transverse fibers of dorsum of interossei, 8 = oblique fibers of dorsum, 9 = lateral band of extensor tendon, 10 = central or middle band of extensor tendon, 11 = central or middle band of interosseous tendon, 12 = lateral band of interosseous tendon, 13 = oblique retinacular ligament, 14 = central or middle extensor tendon, 15 = spiral fibers, 16 = transverse retinacular ligament, 17 = lateral extensor tendon, 18 = triangular ligament (or lamina), 19 = terminal extensor tendon, 20 = flexor superficialis tendon, 21 = flexor profundus tendon.

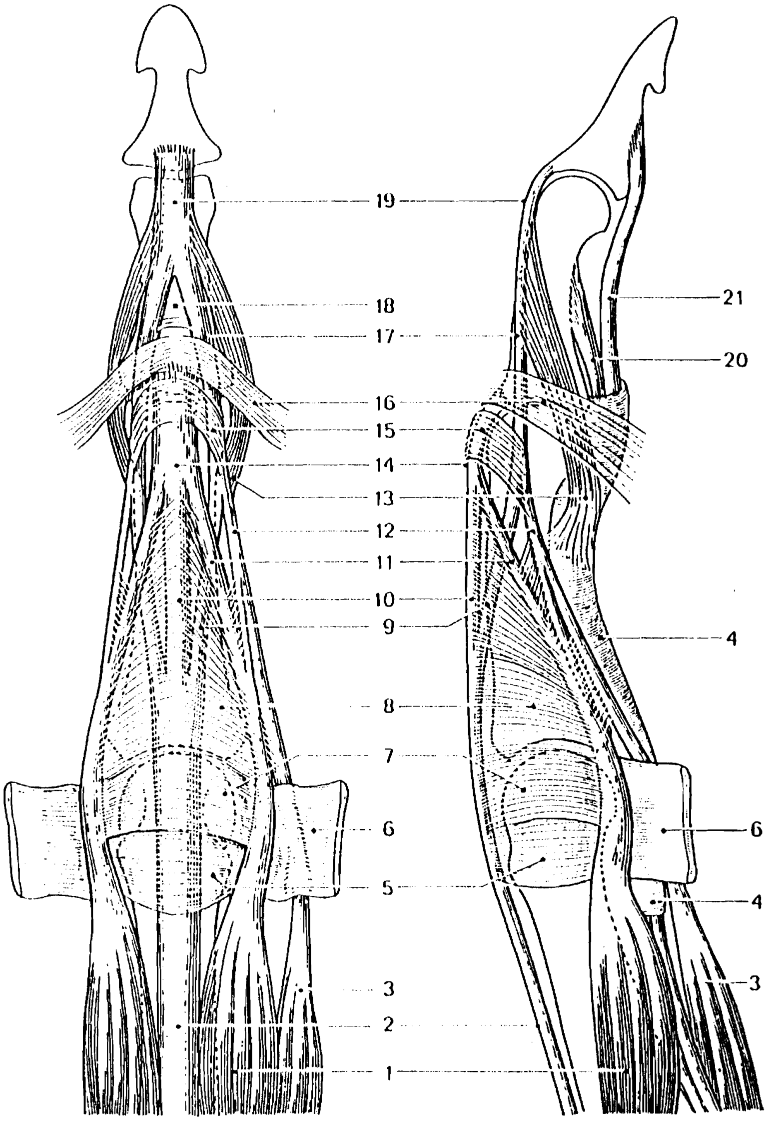

Figure 1: Lateral and dorsal views of a finger

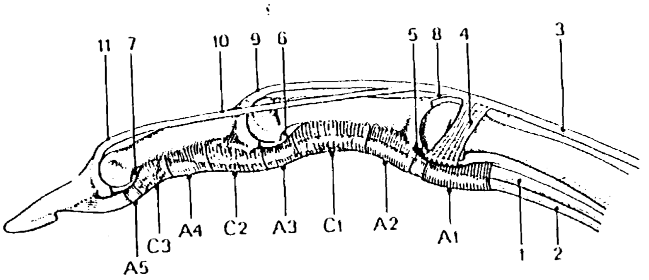

Figure 3–1. The extrinsic tendons of the fingers. In each finger, the superficial (1) and deep (2) tendons surrounded by their synovial sheath are closely applied to the phalanges by their fibrous sheath. These include five annular pulleys (A1, A2, A3, A4, A5) and three cruciform portions (C1, C2, C3) offering no resistance to joint flexion.

The extensor digitorum communis has five terminal insertions: the most proximal is made up by the sagittal bands (4), which insert to the volar plate (5) on each side of the metacarpophalangeal joint. The insertion at the base of the proximal phalanx is not constant. The insertion of the central (or middle) extensor tendon to the base of the middle phalanx (9) is the most important. Finally, the two lateral extensor tendons insert to the base of the distal phalanx.

1 = Flexor digitorum profundus; 2 = flexor digitorum superficialis; 3 = extensor digitorum communis; 4 = sagittal band inserting to the volar plate of the metacarpophalangeal joint; 5 = volar plate of the metacarpophalangeal joint; 6 = volar plate of the proximal interphalangeal joint; 7 = volar plate of the distal interphalangeal joint; 8 – insertion of the extensor digitorum communis to the base of the proximal phalanx (inconstant); 9 = insertion of the middle extensor tendon to the base of the distal phalanx; 10 = lateral extensor tendon; 11 = terminal extensor tendon inserting to the base of the distal phalanx; A1, A2, A3, A4, A5 = annular fibers of the fibrous sheath of the flexor tendons forming five pulleys; C1, C2, C3 = cruciform portions of the sheath of the flexor tendons.

Figure 2: Tendons and ligaments in finger

by the extrinsic muscles of the digits. The wrist muscles coordinate with the Flexor muscles, primarily due to the routing of the digital Flexor tendons which cross the palm and are aligned with the flexion-extension axis of the wrist. For maximal force to be exerted by the enclosing grasp, the wrist must be in slight extension.

2.1.1 Tendons and Ligaments

The tendons are ideally suited for the task they perform, which is flexing and extending the joints in the fingers. Tendons are incompressible, are inextensible yet flexible, and mechanically resistant. To ease their motion, the tendons are placed in a synovial sheath which contains a lubricant called synovial fluid. Tendons are also well-suited to actuating multiple small joints, where they can be remotely activated by muscles in the base of the hand or even the forearm muscles. They use less volume, since they are flat, and require a smaller radius of bending. They are usually connected to muscle at the proximal end and are inserted into bone or cartilage at the distal end.

The ligaments from the forearm that are brought into the the hand are of two types, each counter-balancing the other. The Flexor Carpi Radi(FCR) and the Flexor Carpi Ulnar(FCU), are the Flexor tendons. The FCR is connected to M2 and M3, while the FCU is connected to M5. The extensors balancing the flexors are the ECRL at M2, the ECRB at M3 and the ECU at M5. The multiple tendons allow the palm to be flexed to comply with different shapes, and varying stiffness.

The Extensor Digitorium and Flexor Digitorium muscles are located at the base of the Metacarpels thus not adding any weight to the fingers. The multiarticular tendons used in the fingers allow the compliant coupling between the distal and middle phalanges providing our excellent enclosing grasp. A Flexor Tendon Sheath runs from Metacarpels to the distal Phalanx, using two pulleys at the proximal and distal phalanx, to prevent bowstringing of the tendon.

2.1.2 The Skin

For its very small volume the hand has a larger skin area than any other part of the body. There are two very specialized skins, the dorsal skin and the palmer skin. Each skin serves a very specific purpose, and like most specialized parts of our bodies, is admirably suited for its task. The palmer skin is a very thick, inelastic and corneous surface. The skin is attached to the bone and the fibrous skeleton, in a rigid manner such that the skin does not *shift* away from the bone in any direction. To increase the fixation of the skin there are dermal insertions by some of the muscles. In the primary contact areas there are layers of fibrous bands, that form a cushion, to help conform to the object contour. These cushions exist on the palmer area of the phalanges, the metacarpal heads and the thenar and hypothenar heads. The finger tips have papillary ridges arranged in concentric whorls, to assist in gripping, and the glandular secretions from the palmer skin increases the adhesion properties of the hand while grasping.

The dorsal skin, on the other hand (no pun intended) is mobile and supple. to aid in the articulate motions of the hand, Its extension is noticeable when we flex the wrist and make a fist. Similarly when we stretch out our thumb, the skin stretches across the webbing, without causing any tension on the muscles.

2.2 The Mobility and sensory capabilities

Many features of the hand work together to provide the multiple compliant degrees of freedom that the hand possess. The extrinsic muscles are one of the primary components that provide this flexibility. We have already elaborated on the suitability of the tendon, for providing mobility to joints. The nerves and vessels are surrounded by loose fibroadiopose connective tissue allowing them to adapt to any stretching or bending that they undergo. The skin at the back of the hand, the dorsal integument, must be able to slide over the Metaphalangeal joints, and the interphalangeal joints, and this is done by having the skin arranged in folds on the dorsum of the different articulation. Thus we can see that in trying to study the hand, one must have a good understanding of each of the various subsystems. Yet is is very difficult at times to understand the couplings with each single subsystem. We show this in the motor system and then look at how the joints articulate relative to each other. Finally we provide a brief description of how the sensory system is embedded within the skin, and its varying sensitivity. cohesive manner.

The extensor apparatus is much more complicated than the Flexor system. here the extrinsic and intrinsic muscles must work in conjunction to accomplish complete extension. The long extensor has insertions in all digits, though they cannot independently control the extensions of all of these joints. The long extensors work primarily on the proximal joint. Two distal joints, have a set of three intrinsic muscles, that allow the some amount of independent control of the two joints. This system, allows us to flex the MCP joint, while keeping the other two joints flexed. Lambeer showed how three muscles can be used to control the articulation of two joints. Both the distal and the proximal phalanx have a three muscle system to control their articulation, thus providing us with contour shaping ability of the fingers in the hand.

2.2.1 Muscular force

The muscles in the hand can be topographically divided into two sets, the extrinsic and the intrinsic. For the articulation of the joints this division has no relevance since each articulation tends to be a function of many muscles. The extrinsic muscles are those that originate in the forearm and end in the hand, while the intrinsic both originate and terminate in the hand.

Various studies have been done to measure and record the musculature of the hand. The most common method used so far has been done by multiplying the cross sectional area of the muscle by some coefficient, which is derived experimentally [Sti51]. This method of calculating the force that can be applied by the muscles has been disputed since cross-sectional areas vary considerably. More recent studies have made use of strain-guage based sensors [lKTPW78, FPK79] yielding figures that are of similar magnitude e.g. for the ECR muscle force between 31 and 17 kgs. Muscle strength in hands are a function of the amplitude of contraction, which is typically one third of its normal length, and the length of the fibers that make up the muscle. Other factors include the gliding of the tendon and the angle the tendon makes with the pulleys on which it hinges. The flexors and the extensors of the wrist have roughly equal strength, whereas the digital flexors are far stronger than the extensors. In the individual digits often the extrinsic

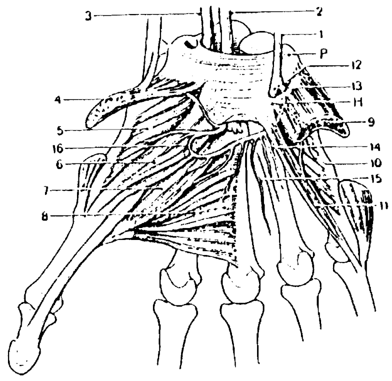

Figure 49-9. Dissection of the palm to show the deep branch of the ulnar nerve. 1, Ulnar nerve. 2, Median nerve. 3, Flexor pollicis longus. 4, Abductor pollicis brevis. 5, Opponens pollicis. 6, Flexor pollicis brevis. 7, Adductor pollicis, oblique fibers. 8, Adductor pollicis, transverse fibers. 9, Abductor digiti minimi. 10, Opponens digiti minimi. 11, Flexor digiti minimi. 12, Motor branch of ulnar nerve. 13, Sensory branch of ulnar nerve. 14, Branches to ulnar two lumbrical muscles. 15, Branches to interosseous muscles (only one shown) 16, Anastomosis between thenar branch of median nerve and deep motor branch of ulnar nerve (anastomosis of Riche and Cannieu). P, Pisiform. H, Hamate.

Figure 3: Extensor tendons and nerves

muscles provide a larger force as in digits 3 and 4, while digits 1 and 5 have stronger intrinsic muscles.

2.3 Articulation of the Joints

The fingers bend inward and radially towards the base of the palm and thumb. The joints in the fingers are driven by the two collateral tendons that are either uniarticulate or multiarticulate. The range of the joints varies in flexion. The MCP joint has a maximum motion of about 85 degrees, whereas the PIP joint can rotate about 115 degrees. Lateral symmetry in the articulations is provided through equal strength of the two collateral ligaments. The MCP joint varies from the other phalangeal joints in that it allows both a certain amount of lateral motion, plus a seldom used slight axial rotation. The base of the proximal phalanx is small and concave, and the metacarpal condoyle which articulates with it allows considerable motion for the phalanx. Since there is much freedom of motion, stability is provided by the MCP ligaments. These ligaments are relaxed in extension, thus allowing far greater mobilty than when the finger is in flexion. The strength of all the fingers in not equal. The forces that can be exerted by the two radial fingers is about 1.5 times the force that can be applied by the two ulnar fingers. In addition, a large part of the grasping forces are applied by the thenar and hypothenar muscles in the palm. The thenar muscles, which are intrinsic muscles, consist of a set of muscles that provide adduction and flexion to both the IP and the MP joint. The extrinsic muscle that flexes the IP and the MP joint is the Flexor pollicis longus.

The thumb rests on the Scaphoid and the trapezium, providing it with two fixed pieces and three articulated components. There are two DOF in the trapezometacarpal joint, two in the carpometacarpel joint, and one in the interphlangeal joint. The thumb seems to be constructed to offer opposition to each and every finger-tip pulp area with its own pulp area. This is accomplished by only three DOF, but any articulation on contact requires the other two degrees of freedom.The TMC joint is driven by the three extrinsic muscles, the abductor pollicis longus, the extensor pollicis brevis, and the extensor pollicis longus. The APL muscle extends the TMC joint to bring the thumb into abduction. The EPB also abducts the metacarpal joint and at the same time extends the MCP joint. The EPL can extend and retroject the thumb. This muscle can extend the thumb beyond the plane of the dorsal part of the hand.

2.3.1 Skin Sensitivity and Sensory Perception

There have numerous subjective studies on the sensitivity of the skin. There are two primary nerves that service the hand, the median nerve and the ulnar nerve.The median nerve innervates the palmer region of the thumb, most of the palm, and the radial digits. The ulnar nerve innervates the palmer regions of the ulnar fingers. These nerves, though plentiful for the skin area covering the hand, are not sufficient for the density of receptors in the hand, causing more than one receptor to be on the same nerve fiber. The sensation is not uniform across the phalanges of the finger and palm. The sensitivity tests applied are for two point discrimination, which varies from being able to detect 2.5mm in the pulp of the thumb, to almost 12 mm for the dorsal parts of the hand.

The skin is organized in layers. The outermost layer, or the epithelial layer, has no blood vessels. the layer is constantly renewed by the dermal layer. The dermal layer has an intricate network of neurovascular papillae. The size of the receptors increases as one goes deeper into the dermis. The matrix of transducers in the skin are arranged both spatially as well as at varying depth as encapsulated receptors. There are five major groups of sensors in the dermis, Merkel/Meissners corpuscles, Krause's corpuscles, Ruffini's corpuscles, Pacinian corpuscles and hair follicles. Pacinary corpuscles are buried deep in the dermis, and provide binary information, and have a low resolution. There are approximately 120 of these corpuscles in one phalanx. The Merkel/Meissners corpuscles provide very high resolution images, with approximately 50 cells/mm^2.

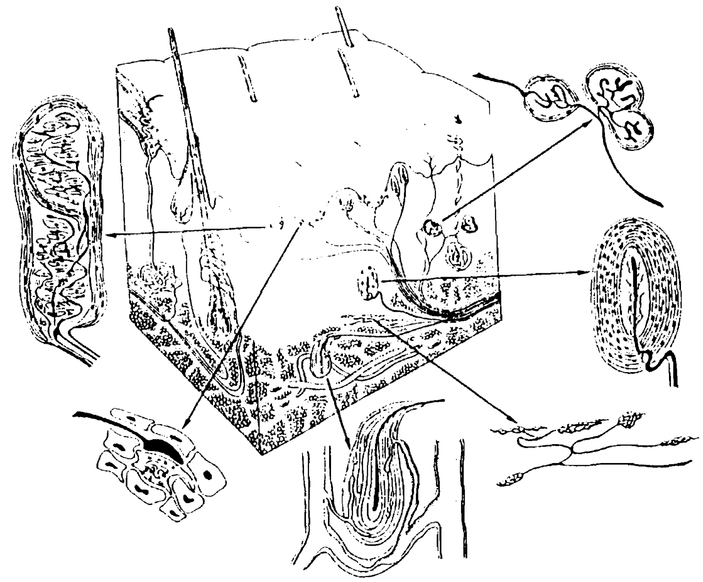

Figure 4: The layers and transducers in the skin

3 The Functions of the Human Hand

To form a broad distinction between human tasks, the word *prehensile* has been used. As the dictionary indicates, prehensile refers to attains to containment or grasping. Non-prehensile tasks would then by definition be any other tasks that the hand performs. In order to clearly demonstrate the difference, we provide a few examples. The lifting of a suitcase is not a prehensile task. In fact, the lifting of the suitcase is done primarily by the arm and shoulder. The hand assists in this task by performing the prehensile task of grasping the handle. While carrying a large box, again the arm and the shoulders do most of the work, the hand merely provides a large surface area, to contact the object, providing friction, and a lever arm, to assist in the manipulation of the box. This supporting activity of the hand would be termed a non-prehensile motion.

Most of the work done in categorizing the functions of the hand, has been done by investigating at the prehensile motions. Little has been done in understanding the non-prehensile task, except in the case of looking at the motions hands perform to extract information from the environment. This kind of information is known as haptic information and the motions, have been termed exploratory procedures [Led87].

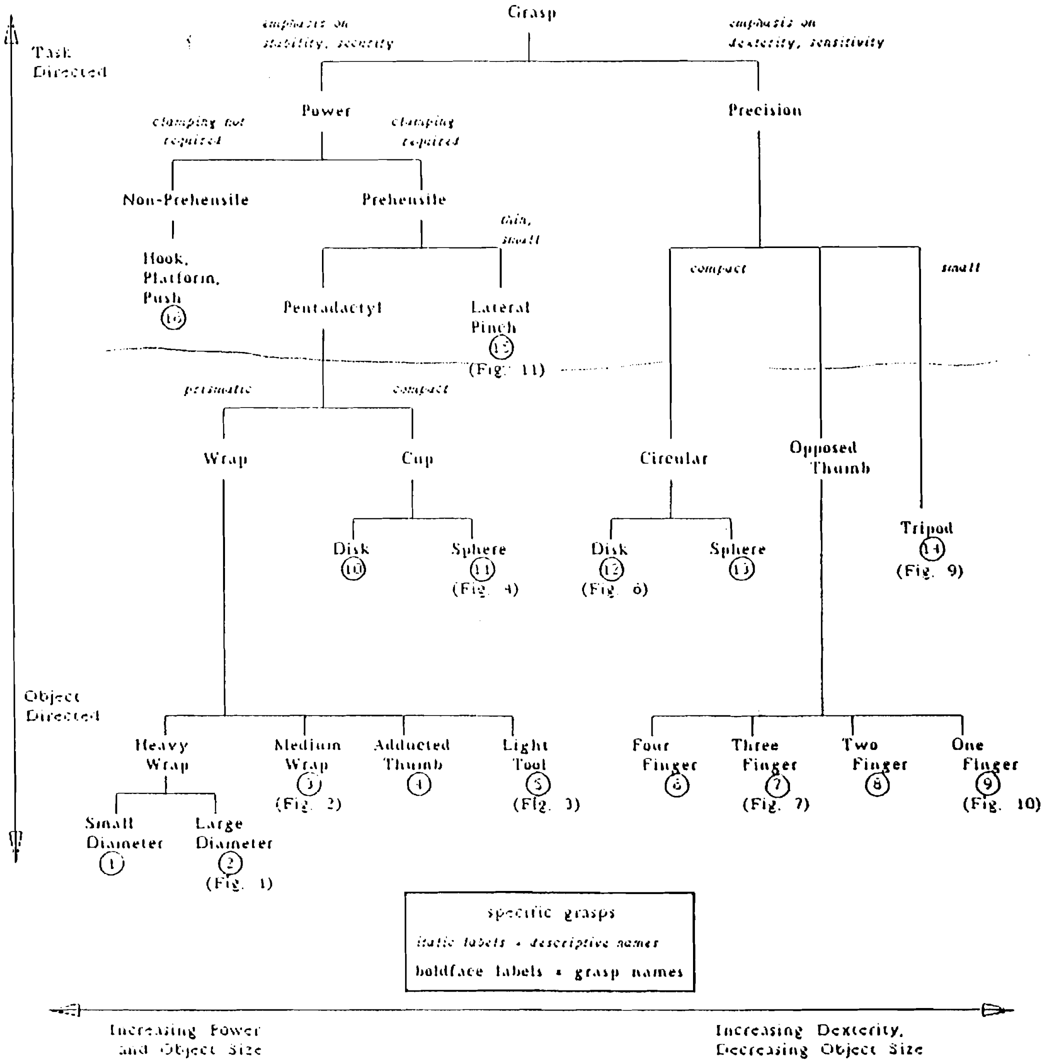

Figure 5: Cutkosky and Wright's Grasp classification

3.1 Prehensile categories

Categorization of the prehensile functions have been done by creating families of grips, using subjective techniques. Some the earliest work was by by McBride [McB80] who suggested that the basis for the differences is the parts of the hand used in the grasp. He had three categories of grasps: using the entire hand, using the thumb and the index finger, and using the palm and the digits. Griffiths has a different criteria for defining his grasps. He uses two principles, the shape of the object being grasped and the final configuration of the hand. Schlesinger in 1919 came up with six grips. His work was studied by Taylor and Schwarz, and describes the grasps, to be cylindrical, tip, hook, palmer, spherical and lateral. Again, his scheme puts less emphasis on the task and more on the geometry. Napier, whose work we look at in detail, completely discards the notion of shape being a criteria for defining tasks. He attempts to make a basis for *the* task as a basis for categorizing prehension. Cutkosky [Cut85], attempt to build a taxonomy of grasps that they claim, will be useful to describe tasks in manufacturing environments. The taxonomy is structured as a bifurcated tree where the first two nodes in the tree, precision and power grasp are taken from Napier, while the motion down the tree in each of these two branches is based on Schlesinger's work on how object geometry plays a role in the grasp type. The taxonomy, though very complete, tends to be very rigid in nature.

3.2 Experiments in Grasping

Work on grasping and the functions of the hand has been studied within the areas of psychophysics and physiology. Westling and Johansson [WJ84] study the factors that influence the choice of forces while grasping. This research is based on experimental data obtained using human subjects. The results that they present lead to some interesting claims. They attempt to show that humans obtain and use information about both the frictional properties of the surface they contact while gripping, as well as the weight of the object. It seems fairly intuitive that humans grip with a slightly larger force than is required to hold the object stably. They define this safety margin as the difference between the gripping force and the slip force. They show by experimental data that this margin is a constant fraction of the gripping force. They also claim that the slip force, and the load forces were proportionate. The final analytical conclusion they draw shows the safety margin increasing with the slip force. Other conclusions they draw are the fact that anesthesing the gripping digits produces no hindrance to reacting to the load of the object while lifting, but reduces the ability of the subject to sense any change in frictional properties of the gripping surfaces. A study was also made to show how one hand can store information about the object, including its frictional and load properties, which the other hand automatically recalls when dealing with the same object. This is an interesting result, as in it tells us that while grasping an object we are recording and storing some of its attributes, that we can use when later grasping the same object.

3.3 Napier's Grasp classification

Napier divides tasks performed by the hand into prehensile or non-prehensile actions. Prehensile actions would include any grasping, enclosing or pinching motions, where the primary activity of the fingers is flexion and that of the thumb is to oppose the motion, with the palm often used to stabilize the motion. Non-prehensile actions use one or more digits to perform exploratory motions, like pushing, pressing, poking, or lifting, using a hook configuration.

The primary objectives to be achieved by prehensile grasps are the security of the grasp. This objective is to be achieved immaterial of whether it can be moved freely or not. Napier claims the next objective in prehensile actions to be the stability of the grasp.

Grasps are divided into one of two categories: power grasps and precision grasps. In the power grasp, the fingers are flexed around the object which, is then pressed into the palm and the thumb is adducted to provide counter pressure. The thumb is often used in abduction when wrapping the hand around an object, with the greater the abduction, the more the power in the grasp. In the precision grasp the finger tip pulps are used with the thumb usually abducted to oppose the force. The assertions made by Napier are backed primarily by examples using objects with different shapes and sizes, which he uses to illustrate the differences in the two kinds of grips.

Napier disdains the claim that grips are a function of the shape of the object. He feels that such categorization fails when we notice the fact that the grip could alter substantially if the task being performed with the grasped object changes. This fact is illustrated in the task of opening the lid of a jar. Initially the lid is gripped with the palm flat on the lid, the fingers flexed around the lid, and the thumb adducted along the plane of the lid. Once the lid starts unscrewing, large gripping forces are no longer required to be applied to the lid. In fact it is not possible to allow any translational or rotational motions on objects that are held in a power grip. Thus the grip changes to a precision grip, with the palm not in contact with the object, and the thumb abducted away from the index finger.

Most actions do have some measure of power and precision, but one of the two attributes seems overwhelmingly dominant. In the power grip, the gripping force and the position of the thumb is used to vary the precision of the grasp. When the thumb is aligned along the plane of the dorsal aspect of the hand, it can be used to provide more precision in the task, albeit at the expense of some power. As the thumb abducts away from the index finger, the grasp can be tightened loosing some dexterity in the bargain.

The object size at times violates the grasp type chosen to handle the object. A large sphere is best held between the thumb and the four widespread finger tips, whereas a smaller sphere is best held by holding it against the palm. The overlap between power and precision grips seems to be greater in the case where objects of extreme size are held with a precision grip, because they cannot easily be enclosed in a power grip.

Napier further talks about the wrist position, as a function of the kind of grasp being used. He claims that the wrist tends to be slightly deviated to the ulnar side, while it is held loosely between flexion and extension during a power grip. This position of the wrist allows the thumb to be aligned along the axis of the forearm when the thumb is adducted, as well as provide mobility in the wrist.

In the precision grip, the wrist is more dorsiflexed, and the wrist is not deviated ulnarly. this position provides stiffness required to more accurately control the position of the hand.

Napier then tries to explains the hook grasp, which he claims is essentially similar to a prehensile grip, but makes no use of the thumb. Here the primary purpose would not be to provide mechanical stability, but instead to stabilize the hold on objects using the structural integrity of the hold. Hooking actions would include lifting, hefting and pulling kinds of motions.

4 Non-prehensile Tasks

The human hand is not unique in the biological world in its ability to function as an active sensor. There are similar devices: the tentacles of an octopus, the trunk of an elephant, and the beak of a bird, or the tongue of a frog. We are constantly amazed at its dexterity, because unlike most of the other similar organs noted above, it has an extensive neuromuscular and sensory system built into it. Thus it is the most articulate part of the human body, with 19 DOF and covered with a skin, which can differentiate texture differential of .3 mm. The hand can be used to break a block of ice, and still open the tightest knot. Both the tasks mentioned above are non-prehensile tasks. It is quite difficult to categorize non-prehensile tasks the way we can categorize prehensile tasks, since non-prehensile tasks are very ill defined in general. One category of non-prehensile tasks that have been focused on is the ability of the hand to get sensory information. There are other categories like synchronized motion, used in typing or playing the piano or violin, which have also been studied [Gal80]. In this paper we focus on some of the work done by Lederman and Klatzky [KLR89], since manipulator design and control would need to take into account such classes of motion in order to provide a wider subset of human capabilities.

4.1 Haptics

There have been substantial studies performed to help understand the relation between our sensory and manipulatory systems. In anatomic studies on animals, it has been determined that nervomuscular system interacts at many different levels with both the sensorial system and the proprioceptive system. This shows us that our ability to manipulate the environment is strongly coupled with our ability to learn about it. Lederman and Klatzky have put forth the theory that there are distinct classes of motions that humans perform with their hands in order to extract information from the environment. They term these motions as Exploratory Procedures(EP). Most of these motions would fall under the non-prehension category, as defined by Napier. The EP's defined are: lateral motion, pressure, static contact, unsupported holding, enclosure, contour following, part motion test and function test. The extraction of information is accomplished by the use kinesthetic and tactile feedback to drive the hand. This would imply some built in cognitive ability to to use the feedback and plan the next motion to complete the EP. An interesting result of the experiments, was the recognition of the fact, that with some objects, it was possible to learn a lot about the object by a enclosure grasp of the object. EP's are more useful to extract specialized information about the object and are only brought into play when such information is desirable.

5 Transition from Human to Mechanical Hands

The initial idea of creating an entity with capabilities similar to the human hand, or with capabilities to augment human hands, must have been the founded in the design of early tools. Now we have already referred to tools used by humanoids, and through the history of man, tools have kept evolving into more and more sophisticated implements. The other drive towards mimicking the capabilities of the human hand came from the desire to provide handicapped people the use of missing or deformed limbs. This area of medicine is nowadays often termed as rehabilitation or reconstruction surgery. In the early days, when the lack of understanding of the anatomy of the hand prevented any sophisticated surgery, the primary goal was directed towards providing the person with a basic prehension capability.

Interest in prosthesis and rehabilatation surgery gained a large impetus during WWI, where a large numbers of hand injuries required that some more creative solution be found. Amputation at the wrist or forearm was no longer necessary, since in cases of infection, there was greater availability of antibiotics, and the spread of infection could be contained.

With mutated limbs, reconstruction of the hand, using existing anatomical features, was supplemented by a prosthesis. Prostheses have been employed since quite early on this century but were never part of the reconstruction and were little more than a brace that was placed, around the mutated limb with a fixed claw at the end.

In the development of prosthesis, the human hand itself presented some of the solutions and directions. The hand as explained later, has a set of powerful extrinsic muscles, that control its functions. These muscles originate in the arm, and forearm. Thus in building an external prosthetic device, a shoulder or elbow harness was built, using the action of the arm muscles to articulate the fingers, or claws in the prosthesis. Since the fingers are very specialized in the way the tendons are routed and connected, it was considered impossible to build implants that could be used to replace mutilated muscles. Thus most reconstruction was performed on the extrinsic muscles.

Later in the century after WWII much more sophisticated techniques were used to reconstruct tendons, graft skin and bones, and control the movements of the tendons using myoelectric impulses from the neuro-muscular system. At the same time as the more sophisticated prosthesis were being built the need arose for tele-operated hands.. With the development of hazardous working conditions, the need to perform remote tasks, helped in the development of devices with a limited number of DOF's but at the same time ease of control. The similarities between mechanical prosthesis and a tele-operator driven slave gripper were largely in the prehensile capabilities. Actuation of tele-operation devices was done by very skilled human operators, the term user friendly was not yet invented. Thus the design issues for prostheses and tele-operated grippers were quite distinct. The design of tele-operated hands was primarily based on the function to be performed. There was little if any feedback other than a visual indication of the interaction of the slave gripper and the object. A number a prosthesis with bio-electric interfaces were designed [Kat69]. These hands were capable of upto three degrees of freedom, but provided mainly prehensile capabilities with limited kinesthetic feedback. Thus even though improvements in the kinesthetic feedback to the operator were made both in tele-operator systems and in prosthetics over the years, few abilities of the human hand were able to be duplicated in any one mechanism.

At the same time robot arms were being designed which needed end-effectors to grasp objects. Using the human model of prehension, pinching using thumb and index finger, the parallel jaw gripper evolved. Versatility in gripper design moved in the direction of providing specialty in the design based on the task, requiring the use of multiple effectors for different objects or tasks. In 1945, Taylor et al wrote that if a mechanical hand could achieve Schlesinger's six grasps configurations, then it would be nearly as adaptive as the human hand. Here Taylor refers to the prehensile capabilities of the human hand.

6 Articulate Hands

The study of articulate hands as a mechanical system spawned many disciplines, though mechanical engineers provided the initial feasible designs. Going from a single DOF parallel jaw gripper to a multiple jointed, multi-linked hand meant overcoming numerous constraints. The problem started with devising something small, light and simple, but with the ability to exert large forces and constrain large objects. Thus it required a multi-disciplinary effort to create feasible mechanical system that could be utilized to perform a variety of tasks. Such articulate electromechanical hands that were computer controlled emerged in the early 1970's. The design criteria for multi-fingered hands is described in a paper by Skinner [Ski75]. He wanted to be able to grasp the basic shapes including spheres, cylinders, and rectangular and triangular prisms. Grasps types required to hold these object shapes, could be subsumed by allow for a variety of prehension modes as defined by Schlesinger. He defined the mechanical equivalents of these six grasp types and felt that three fingers would be sufficient to provide the grasp types.

6.1 Skinners Design

Skinner starts off by defining each finger to be an open linkage, with two or more joints per finger. An increase in the number of joints in each finger would increase the ability of the hand to constrain an object. He considered motors to be the best suited actuators, and these felt the motors should be mounted at the base of the fingers or under the palm. He wanted these motors to be decoupled from the environment, and to be able to measure the rotation of the shaft. He also wanted to be able to control multiple motors using the same signal if necessary. Today this last requirement seems unnecessary as it could easily be programmed in software.

The hand would consist of the three identical fingers, each of which was an open kinematic chain consisting of two joints. The fingers were placed in the corners of the palm shaped as an equilateral triangle.

The joints in the fingers were to be one degree of freedom revolute joints, and two of the fingers were allowed a coupled rotary motion about the axis of the finger. The two joints of the fingers had a coupled motion, allowing for flexion and extension of the two joints in a coordinated manner. The drive

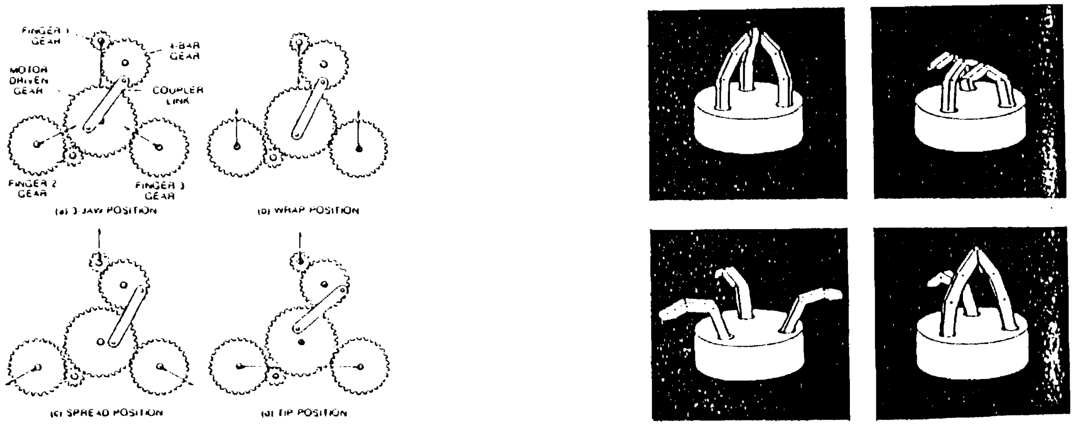

Figure 6: Double-Dwell mechanism, and grasp configurations

mechanism used to move the coupled joints was a cross four bar chain. The third finger was coupled to the other two using a double-dwell mechanism. This mechanism allows for the three fingers to have one of four configurations, the three-jaw, pinch, wrap and spread. These terms would correspond to what we term as spherical, tip, and cylindrical respectively. The spread grasp is unknown in literature since Skinner's paper and thus does have a corresponding term. Skinner used four motors and four control inputs to drive the joints of the hand.

There were many versions of this hand designed, but only the one described above was successfully implemented. It was known as the MPPS industrial hand.

6.2 Other Articulated Hands

Concurrently with Skinner, other hands articulate hands were being designed. The primary motivation for all these hands seems to be providing versatility in grasping. Among these were hands designed by Asada, Mori, Rovetta and Okada [Asa77, Mor80, Rov77, Oka82]. These hands were designed to not only grasp objects, but to also manipulate the objects within the grasp. Various analyses were used, including modeling the fingers as springs. It was often assumed that each contact was a point contact in order to simplify the equations used to decide if the object could be moved within the grasp, or if it had been stably grasped to start with. The lack of sensory feedback was one clear problem while attempting to perform an analysis of how the fingers were interacting with the object. Thus manipulators were now able to grasp a variety of objects with what Napier termed the power grasp, but still had difficulty in performing even the semblance of a precision grip.

7 Issues in Designing a Hand

In 1982 a workshop on dextrous hands was organized at the AI labs in MIT [Hol84]. It was attended by most of the well known researchers in the area who were based in the United States. The debated on the directions to be adopted in furthering the research in designing and building articulated hands. Since the expertise came from a wide range of areas the discussions also covered substantial grounds and brought forth a varied viewpoints. A summary of some of the interesting discussions is provided below.

7.1 Biological versus Non-biological Model

It was argued that biological systems provide us with the best known model, thus an understanding of the system and designs along anthropomorphic lines would be useful in constructing such hands, even if the final hands were not quite the same. Against this philosophy was argued that duplicating the human hand, may not be best suited to the tasks which the manipulator would need to perform, and thus it would be best to let the tasks required to be accomplished drive the design criteria.

7.2 Actuation

Several criteria of actuation mechanisms were discussed including weight, size torque and stall power. The key choices were electro-hydraulic motors and electric motors. Hydraulic actuators were prone to seal friction, leakage at high flow rates and particle contamination. Electric motors, had other problems, including size to power ratio and low magnetic field strength. motors.

7.3 Transmission

Common modes of actuation include gears, drive axles, tendon/pulley systems, lead screws and chains. Direct drive was infeasible because of weight limitations at the fingers. Thus the discussion centered on remote actuation using tendons. Steel cables need large bending radii and routing pulleys to allow the cable to pass through the joints. These pulleys were prone to slip especially if they are not pre-tensioned. Tapes were considered as a better source of tendon material. They were said to have a lower bending radius, less prone to fatigue because they were flat, and could also be sealed in a lubricated sheath. Tendon routing paths could be built into the finger design itself, with low wear surfaces, and at the same time providing a place for wiring to be run through too.

7.4 Kinematic Design

The notion of hole and voids was introduced. If the workspace of the robot was to be considered a toroid, a void would be an empty space in the toroid, while a hole would be the center. To reduce voids, the number of joints in a finger could be made larger, while by making the length of the distal link larger than the proximal ones, the size of the hole could be reduced. The number of links required for a joint was considered using the human model. The debate was whether the all 4 links was used or not, and it was considered sufficient to have three links, thus providing 3 DOF's. The possibility of having a fourth and fifth digit was considered. The claim being that having two extra fingers provides extra stability in the power grasp, and increased dexterity in the precision grasp. Dexterity in the precision grasp would be obtained by allowing for increased number of contact points to retrain the object, as well the greater flexibility to impart torques on the object. With more than three contacts the object could be held stably with three contacts, while repositioning the remaining fingers.

The number of tendons used to control the joints, focused on the n + 1 rule, which states that a n DOF linkage, needs only n + 1 tendons to control each joint independent of the others. It was noted devices built using the n + 1 rule tend to exhibit buckling problems and other instability problems, thus having a number of tendons somewhere between 2n and n + 1 would be better.

7.5 Skin

Soft deformable materials were considered useful for their ability to provide large frictional forces, comply to object shapes, and better indicate the surface shape than point contacts. Rigid skins would assist better in getting exact contact information, as well as provide more sensitivity to tactile feedback. Finger shape could not be resolved, as this aspect was considered too task dependent.

8 Kinematic Analysis of Articulated hands

Much work has been done in the area of kinematic analysis of multifingered hands. Most of the analysis is done on three or four fingered hands, with two to four independently controlled joints. Seminal work in the area was instigated by Salisbury [Sal82] who introduced the notions of using contact freedoms, to define the forces and motions that could be applied to grasped objects. His work focuses on need to be able to immobilize an object in the grasp or apply any desired wrench or twist on a stably held object in a controlled manner. To be able to design and control such a hand, he leads us through a series of steps, where he first lays down the basis for a well suited design and then shows how a hand built using the design synthesis can be used to achieve the desired objectives. We will first explain the contact types Salisbury defines and relate the contacts to the DOF that they possess. We explain twists and wrenches and how the DOF can be mapped onto a reciprocal set of twists and wrenches. We then use this basis to define the number of contacts required to provide a *connectivity* of both 0 and 6, between the hand and the object.

8.0.1 Contact types and their connectedness.

A contact is defined two contiguous areas that touch each other. There are 6 type of contact types defined: a point contact, a point contact with friction, a line contact, a line contact with friction, a soft finger contact, and a planar contact with friction. The contact type limits the set of motions and forces that the body can experience relative to each other. These restrictions are based on the number of freedoms that the contact type allows. The freedoms range from 0 in the case of a planar contact with friction, to 5 in the case of a point contact with no friction. The contact normal is defined as the line along the outward pointing normal of the tangent plane of contact. A single contact normal between the two bodies will be sufficient, since the directional sense of the contact normal is not important.

In order to describe the contact freedoms, Salisbury uses screw representations of forces and motions. A screw is defined by a line in space and a pitch. The direction of the line is the axis of the screw. Screws are defined by a six vector of screw coordinates. The twist defines infinitesimal motion of a body in space, with the twist axis defining the direction of translation, and the axis around which the body would rotate. The pitch of the twist, is the ratio of the magnitude of the velocity of a point along the twist axis, to the magnitude of the angular velocity about the twist axis. By this definition a zero pitch twist constitutes a pure rotation and infinite pitch a pure translation.

A wrench is also represented by a screw, with the equivalent force acting along the wrench axis, and the equivalent moment acting about the wrench axis. The pitch of the wrench is the ratio of the magnitude of the moment applied around a point on the axis, to the magnitude of the force applied along the axis. Thus by definition, a zero pitch, implies a pure force wrench, while an infinite pitch wrench implies a pure moment.

Two screws are reciprocal if their virtual number is zero. The virtual coefficient can be defined as the rate of work bone by the wrench $\underline{w}$ on a body moving with a twist $\underline{t}$. A reciprocal screw system can perform no work on the body. An ensemble of screws is known as a screw system. The order of screw system n, is equal to the number of basis screw required to define it.

8.0.2 Hand Design

Salisbury [Sal84] defines the term *degree of freedom* of a joint, to mean the number of independent parameters needed to completely describe the motion between the two bodies connected by the joint. These freedoms are termed passive, since they cannot be actively controlled.

The *Mobility* of the system is the number of parameters required to specify the location of every link in the kinematic system. The*Connectivity* between any two links in the system is the number of independent parameters required to specify the relative position or set of positions between two links.

For a satisfactory hand design, the hand should be able to impart arbitrarily directed forces and velocities on the object, or to constraint an object completely. To constrain the object the connectivity between the reference frame and the object must be zero, and in the other case, the connectivity should be six. Hand designs examined allowing 2 or 3 fingers with upto 3 joints per finger produced 120 configurations. If each of these designs was considered with contact types varying from one DOF to 5 DOF there would be 600 designs to choose from. Only 39 of these designs were found to possess, a connectivity of 6 with the joints active C and a connectivity of 0 with all the joints locked C'.

Of these 39, the 33 assuming 5 DOF contacts were rejected because it was determined that 5 DOF contacts, do not allow moments to be exerted on arbitrary objects. Of the remaining 6 designs, that satisfied the C and C' requirements, one design a three fingered hand with three joints in each finger and contacts assumed to be 3-freedom contacts, was able to overconstrain the object with the joints locked. This was considered advantages since it would allow for the constrain of internal forces in addition to restraining the object. The contact was assumed to be occurring on the last link, and since the contact was modeled as a point contact with friction, the finger was to be designed with a hemispherical tip.

8.1 The Stanford/JPL hand

Using the above criteria to design a hand [SR83], Salisbury built what is arguably still the best hand for performing dextrous tasks. There are three fingers, each with three joints. The joints are driven by tendons, which are teflon coated steel tendons, that pass through tendon coated conduits. These cables are taken out of the hand, and passed into a remotizer, that can be mounted on the robot forearm. The number of actuators used was a crucial design decision. The minimum number of actuators required to independently control the individual joints is n + 1 [Mor80]. 2n actuators would allow independent stiffness and torque control. Salisbury chose to design modular fingers using 4 tendons and 4 actuators per finger. The three independent finger actuators also allow for modular control and mechanical cross coupling between fingers. At the base of the fingers, there is an idler pulley, mounted on a strain guage beam that can be used to measure the tendon tension, and thus the force exerted at the finger tip. In position control the joints are controlled using a simple relation between joint velocities and tendon velocities. R is a 4 X 4 constant matrix that relates m joint angular velocity with t tendon velocity. Thus we can derive the moment applied at the tip using (1) and (2).

$$m = Rt \ (1)$$

$$t = R^{-1}m \ (2)$$

The velocity of the finger tips, can also be related to the joint angular velocity using the transpose of R, R^T.

$$v = R^T w \ (3)$$

$$w = R^{-T} v \ (4)$$

In order to actuate the joints we relate the desired joint angle, to the desired tendon position. Integrating equation 3 and 4 over time we get

$$x = R^T \theta + x - o \ (5)$$

$$\theta = (R^{-T})x - x - o) \ (6)$$

where x is the 4X1 tendon position vector, θ is the 4X1, joint position vector x_o is the initial tendon position The joint controller hardware consists of 12 8086 Microprocessors, each controlling one of the actuators. A VAX 11/750 communicates directly with these boards, sending them a new set point every 20msec. The 8086 boards run at a servo rate of 1000hz, using a proportional derivative position controller to interpolate between the set points. Tendon stretching errors are ignored.

A vector of 12 set points is sent to the high level controller, which then smoothes out the trajectory, between segments. The velocity profile is also smoothened, as is the coordination between desired joint acceleration. The maximum time required to accelerate is determined among all the joints, and the acceleration profiles of the rest of the joints is reduced, to allow for a coordinated profile.

8.2 The Utah/MIT hand

An almost anthropomorphic hand [JWKB85], the Utah/MIT hand was designed as a research tool with no intention of ever being used as an industrial device. It is a four fingered hand, with four joints per finger. The thumb is opposed to the fingers, though placed in the palm, instead of on the side. Each joint is activated by two independent actuators to allow independent control of both torque and stiffness at each joint. The tendons are flat, and are routed thought he hand via pulleys and using axial twists. The tendons are brought out of the hand and into the remotizer unit which must be mounted elsewhere. The actuation system of the Utah/MIT hand has a pneumatic valve with an integrated pressure control loop. The actuators are used as antagonistic pairs and provide a high bandwidth, low output impedance system. There are dampers applied that allow the stiffness of the actuators to be better controlled. The joint angles are sensed using hall effect sensors, and the tendon tension sensor is located in the wrist and uses a bending beam strain guage sensor. The low level control has 16 variable-loop-gain position servos, and 32 variable-loop-gain force sensors. This is accomplished using five Motorolla 68000 processors, a Multibus card Cage, 40 Channels of D/A and 320 A/D channels. The system needs over a 100 inputs into the joint controllers to servo the hand and can be interfaced to higher level controllers using a Multibus.

9 Conclusion

Our understanding of how hands work and their capabilities has not increased by much over the last few decades. What has changed is our knowledge of the functionality of the hand. In order to build mechanical systems that can behave like human hands we need to understand the underlying mechanisms used by the human hand to perform its tasks. Since human system behavior is dependent on many factors, we would have a combinatorial explosion of possible actions unless we can define a set of underlying primitives that the system uses to perform its tasks. In the case of the human hand, these underlying primitives can be defined based on the musculature for a subset of actions, namely prehensile. But firstly this set of primitives are incomplete, and secondly the primitives are not well defined. It seems that in this time, we have not been able to derive a better set of primitives, or even a more extensive set of primitives.

9.1 Hardware and sensors

We have certainly come a long way in our ability to build mechanical devices that can mimic the articulations of the human hand. Hands have been built that have three fingers and an opposing thumb, with each linkage having upto four joints. Even the human transmission system has been duplicated by using tendons to drive the joints, one tendon for flexion, another for the extension of each joint. In the other areas of the anatomy of the hand, we are sadly lacking. The neurological system is particularly difficult to emulate, since it relies on a complex network of pathways for signals that must be able to physically comply with the motions of the hand. These pathways are intrinsic to any sensory system, since they allow the signals obtained from the source to be combined, pre-processed and carried back to a central site. Much greater advances have been made in the area of building transducers for extracting sensory information from the environment. Sensors have been designed that have a resolution of .5mm, that can measure shear forces, and measure moments as well as normal forces. These sensors often have a resolution of upto 8 bits.

The transducers are often built in an manner, that requires tiresome wiring prone to noise, and possessing very stiff surfaces. In addition most sensors are rarely tested in conjunction with an articulated mechanism to allow for the integration of the sensory data into the control of the mechanism.

One further step in the area of sensor development is to provide skin like characteristics to the surface of the sensor. We would like to lower its stiffness, increase the friction, and at the same time provide the same resolution in the response of the sensors.

A crucial problem that is faced in building specialized or sophisticated technologies in separate areas is our inability to merge them to build a system that can function in a coordinated manner. Highly articulated hands are the only mechanisms that can make use of such high resolution sensors. It is pointless to have sensors which have extremely high bandwidth and resolution mounted on a slow manipulator with a limited number of DOF. At the same time using an articulated hand using only force torque sensors, makes it only as useful as a parallel jaw gripper. Thus the crucial task left in the hardware development of articulated hands must be the integration of sophisticated sensors in articulated mechanisms. As Harmon [Har82] put it, almost all our senses react to externally radiated energy except for touch and kinesthetic feedback. Thus for these senses to be used in a meaningful manner, we must be able to articulately use our hands and provide the necessary input for performing any related task.

9.2 Mid-level Control

At this point we bring the notion of mid-level control for the use of articulated hands. There has been some recognition of this idea in the area of neurobiology [EC84], by showing how some of these mid-level functions emerge in children. We can define mid-level control as the framework that allows a high-level task to be sub-divided into segments that are performed in succession or in parallel to complete the task. The boundaries of these segments are not clearly defined, in that they essentially fall into one another, but each segment couples the sensory and manipulative system in a particular manner. Pao [PS85] used a glove which measured displacements in the joints in the fingers and mapped these displacements into the joint space of the Utah/MIT hand. This mapping scheme was used to teach the hand several coordinated finger motions used in performing a variety of tasks. These coordinated motions form a segment in the mid-level control, however these motions, were based purely on position control and not much use in actually performing a task.

Conscious understanding of the motions performed by our hands is difficult at best and impossible at worst. Considering the high bandwidth at which typists can move their fingers across a keyboard, it is not difficult to see why the above statement can be taken at face value at present. But this ability of the human hand to control its low-level behavior in an extremely adaptive manner given its task framework is exactly the ability we would like to provide articulate hands with.

Since the task framework under which the hand is performing its motions is fairly rigid, the adaptability of the hand must come from its changing interaction with the environment. These changes are first and foremost detected by our force/tactile sensors and fed back to the neuromuscular system which must adapt to this feedback in a manner dictated by the current segment framework. This kind of adaptation implies a very flexible framework at the segment level, allowing for a wide range of contacts and forces to be controlled and adapted to.

Creating these segment frameworks is fundamentally a complex problem, that is beyond simply solving the kinematics, or the grasp stability or controlling the stiffness of the system. In fact, a segment framework would have multiple laws controlling the motions of the fingers, each trying to achieve one objective, with each law being given a higher priority that would be stipulated in the segment framework.

The segments provide both the framework needed for data driven manipulation, as well as a means to breakdown a complex task into simpler stagewise motions that could be achieved in a coordinated manner or independently.

9.3 Human Grasping Revisited

Human grasping has been considered the best model for coming up with a design criteria for mechanical hands. But this model has been used entirely in the kinematic and actuation design. The control framework for hands has been borrowed from 6 DOF robot manipulators that never interacted with the environment, had large inertias in the joints, and required little or no sensing to perform a range of useful tasks. The primary purpose of hands is to interact with the environment in a manner which needs to be data driven. We have to realize that without the ability to construct a framework within which we can evaluate the sensory information we receive from robotic hands we will not be able to do much better than pick and place geometrically symmetric objects.

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