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Grasping With Mechanical Intelligence

Abstract

Many robotic hands have been designed and a number have been built. Because of the difficulty of controlling and using complex hands, which usually have nine or more degrees of freedom, the simple one- or two-degree-of-freedom gripper is still the most common robotic end effector. This thesis presents a new category of device: a *medium-complexity* end effector. With three to five degrees of freedom, such a tool is much easier to control and use, as well as more economical, compact and lightweight than complex hands. In order to increase the versatility, it was necessary to identify *grasping primitives* and to implement them in the mechanism. In addition, power and enveloping grasps are stressed over fingertip and precision grasps. The design is based upon analysis of object apprehension types, requisite characteristics for active sensing, and a determination of necessary environmental interactions. Contained in this thesis are the general concepts necessary to the design of a medium-complexity end effector, an analysis of typical performance, and a computer simulation of a grasp planning algorithm specific to this type of mechanism. Finally, some details concerning the UPenn Hand - a tool designed for the research laboratory - are presented.

Comments

University of Pennsylvania Department of Computer and Information Science Technical Report No. MS-CIS-89-51.

**Grasping With Mechanical
Intelligence
(Ph.D. Dissertation)**

**MS-CIS-89-51
GRASP LAB 190**

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contributed the sensors for the UPenn Hand**

UNIVERSITY OF PENNSYLVANIA
SCHOOL OF ENGINEERING AND APPLIED SCIENCE

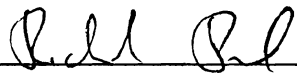
GRASPING WITH MECHANICAL INTELLIGENCE

Nathan Thatcher Ulrich

Philadelphia, Pennsylvania

December 1988

A thesis presented to the Faculty of Engineering and Applied Science of the University of Pennsylvania in partial fulfillment of the requirements for the degree of Master of Science in Engineering for graduate work in Mechanical Engineering and Applied Mechanics.



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(Graduate Group Chair)

Abstract

Many robotic hands have been designed and a number have been built. Because of the difficulty of controlling and using complex hands, which usually have nine or more degrees of freedom, the simple one- or two-degree-of-freedom gripper is still the most common robotic end effector. This thesis presents a new category of device: a *medium-complexity* end effector. With three to five degrees of freedom, such a tool is much easier to control and use, as well as more economical, compact and lightweight than complex hands. In order to increase the versatility, it was necessary to identify *grasping primitives* and to implement them in the mechanism. In addition, power and enveloping grasps are stressed over fingertip and precision grasps. The design is based upon analysis of object apprehension types, requisite characteristics for active sensing, and a determination of necessary environmental interactions. Contained in this thesis are the general concepts necessary to the design of a medium-complexity end effector, an analysis of typical performance, and a computer simulation of a grasp planning algorithm specific to this type of mechanism. Finally, some details concerning the UPenn Hand—a tool designed for the research laboratory—are presented.

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Chapter 1

Introduction

Although robots have become common tools in manufacturing and assembly, their uses have been limited to the repetition of simple fixed tasks. Programmed to perform certain operations over and over, they have little capability to adapt to changes in their working environment. This deficiency of hard automation has resulted in a search for more flexible solutions—robots that can react, learn, and adapt.

An important part of an intelligent system of this type is a combination of mechanisms which form the “body” and comprise a dynamic physical agent for the commands of the “brain.” Human intelligence is generally considered to be a characteristic of the human mind, yet it is the form of our hands which most differentiates us anatomically from other primates. The design of a simple mechanical hand is the subject of this thesis.

Most robots use one of a great variety of end effectors, each specialized for an individual task. Rather than use a single dextrous hand to hold and manipulate objects and tools, the end effector itself is changed. This approach is most efficient in automated manufacturing, where the surroundings are rigidly controlled and the number of tasks is quite limited. In order to expand the use of robots to applications where the environment is dynamic and unpredictable, one versatile end effector is necessary. It should be able to handle tools for specific task categories, but also be

versatile enough for general object manipulation and unplanned operations. Such a mechanism would allow a robot to approach an unfamiliar task in much the way that a human does: with a general-purpose hand, a toolbox, some rudimentary physics, and the ability to learn.

Although such an approach requires duplication of many of the functions of the human hand, it does not necessarily prescribe an exact copy. The components available to the designer of a robot system are very different from those found in the human system. A successful design should use the strengths and avoid the weaknesses of these resources. In order to compensate for a lack of computational intelligence, a greater degree of *mechanical intelligence* is necessary; an intelligent mechanical design can complement limited reasoning capabilities. The designer of a robotic end effector must not only consider the criteria imposed by the application, but also must confront the limitations of current control and planning systems.

Previous Hand Designs

Many mechanical “hands” have been designed. The Stanford/JPL hand, designed by Kenneth Salisbury, was the first to be used widely[1]. The hand has three fingers, each with three joints and three degrees of freedom. Salisbury used numerical analysis techniques to find the optimal palm and finger geometry for fingertip manipulation. Although the hand has been successfully programmed for a number of fine motion tasks, only the fingertips of the hand are used. Such grasps depend on frictional forces to maintain stability. The device has allowed researchers to learn about the movement of small objects within such a fingertip grasp, but it was not designed to explore other types of object apprehension.

The Utah/MIT Dextrous Hand is an imitation of the human hand. It has four fingers, each with four degrees of freedom, and requires a large actuation package of 32 pneumatic cylinders. The actuation is therefore removed from the hand by means

of a “remotizer” which routes the 32 tendons to the base of the manipulator[2]. Research into control and planning techniques will allow the Dextrous Hand to be useful in understanding the human manipulation system, and other applications are being explored.

Another approximately anthropomorphic design is the Belgrade hand. Although originally designed as a prosthetic solution for veterans in Yugoslavia after the Second World War[3], a recent collaboration with the University of Southern California has produced an updated design[4]. It uses one motor per pair of fingers, one motor for the thumb and a set of mechanical linkages to produce cocontraction of finger joints. Another linkage allows the fingers of each pair to move together and to comply to object shape. The new design can be more fully evaluated when it is complete and under computer control.

A previous research effort at the University of Pennsylvania produced the Pennsylvania Articulated Mechanical Hand (PAMH). A unique type of actuation method using lead screws and cams moved three two-jointed fingers. A seventh degree of freedom moved a “thumb” around the palm[5]. It was used for research into tactile sensing and reactive manipulation.

Other hand designs, which have used innovative techniques such as shape memory alloy (SMA) actuation and pneumatic “elephant-trunk” rubber fingers, have been proposed[6]. Although many have been built and tested in research labs, the only end effector in common use is the simple one- or two-degree-of-freedom gripper. This device—in its many variations—has found acceptance because it is robust, economical, simple, and easy to control.

There is a need for a more versatile research tool than these grippers. Theoretical results and progress in other areas of robotics has created an opportunity for a more complex end effector. However, the hands described above are still too cumbersome to use in most applications. A compromise is possible. The ideal general-purpose end effector would combine the versatility of a complex hand with the strength,

robustness, and control simplicity of a simple gripper. Such a solution may require unconventional or previously-ignored approaches to grasping.

Grasping Analysis

In order for an object to be moved from one place to another, it is necessary to consider the interactions between the object and the manipulating device. One approach is to attempt to push objects to the desired configuration[7, 8]. This is a valid strategy in certain situations, but almost any end effector mechanism can perform the function of “pusher.” More demanding of a device is the stable apprehension of an object.

There are two distinct approaches to grasp stability. The most attention has been focused on using three or more fingertips, strategically placed on an object’s surface, for grasping. The dynamics of such a contact situation are quite straightforward, and investigating the conditions of stability and the “manipulability” of a hand design is an active research topic[9].

There are several problems with this approach to grasping. Because seven frictionless point contacts are the minimum necessary to fully constrain an object in space[10], fingertip grasping with less than seven fingers requires frictional forces for stability. The determination of the conditions of contact, the coefficient of friction, and slip detection introduce complications into the analysis. As the weight of the grasped object increases and the coefficient of friction decreases, the contact forces necessary for stability become extremely large. This imposes severe demands upon the grasping mechanism.

In contrast, enveloping grasps use the inner surfaces of the fingers and the palm to contact an object. Because each finger has more than one contact, and the palm has one or more contacts, such grasps can generally constrain an object without friction. This type of grasping has recently received some attention[11]. For many objects, for example, most tools, this is a better grasp because the contact forces are evenly

distributed over the mechanism. In practice, both fingertip and enveloping grasps are useful.

The mathematics used to describe grasping forces and stability is well-represented in the literature. An analysis using these methods is presented in Chapter 5.

Grasp Types and Classifications

Many different classifications of the grasp types used by humans have been proposed. Although a robotic end effector may not use the exact grasping geometry preferred by a human, it is instructive to consider these descriptions. Each type of grasp is a function not only of the size and shape of a given object, but also of the task to be performed. A *power* grasp is usually an enclosure grasp, a grasp that must be able to hold heavy objects or exert large forces. A *precision* grasp generally uses the fingertips for object manipulation, where delicate movement of the object is necessary[12]. The same object could be handled in both types of grasp; a screwdriver could be held in a power grasp for loosening a rusted screw, then in a precision grasp for starting another screw in a threaded hole.

Within these two general categories are various types of grasps which are directly related to the geometry of the grasped object. Iberall cites a number of works which discuss classifications[13]; those of Schlesinger[14] and those of Cutkosky and Wright[15] are most relevant. In 1919, Schlesinger proposed a set of six “prehension modes” which represented those grasps most commonly used by humans. Because of the date of his work, Schlesinger was obviously not considering the application of these modes in robotics research, but they concisely cover the wide range of manipulations possible with the human hand. Figure 1 shows these classifications, where the oval represents the palm of the hand and the heavy lines represent fingers. Each grasp is shown in a top view showing the relationship of the fingers to the palm, then in a side view depicting a hand grasping an object typical of the category.

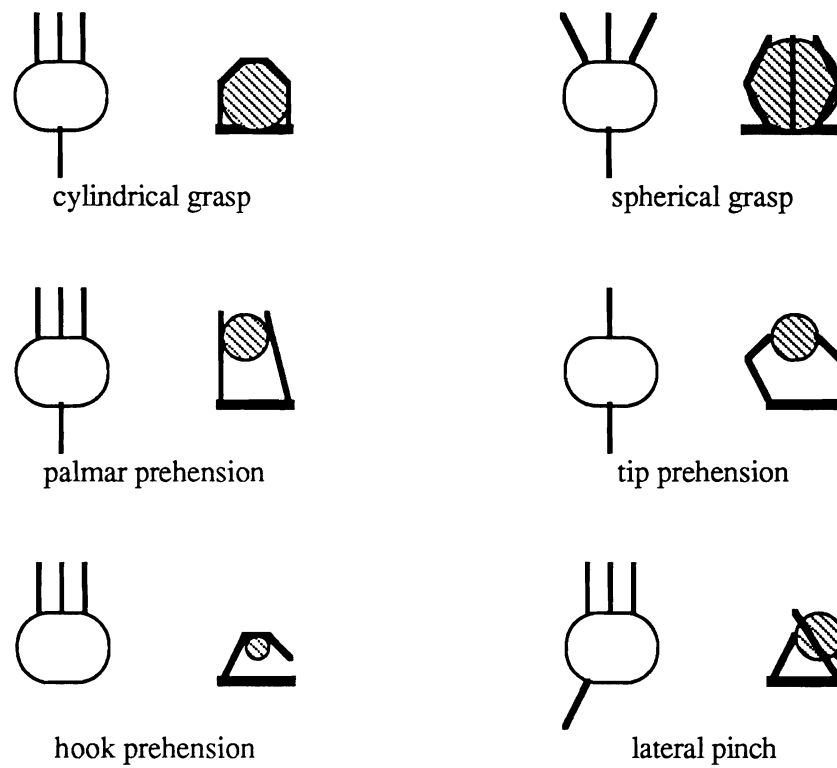


Figure 1: Schlesinger's prehension modes

Schlesinger's prehension modes are general and address only the geometric category of a grasped object. However, it can be seen from the sketches in Figure 1 that the cylindrical, spherical, and hook modes would be used to manipulate heavy objects or perform tasks that require large forces, while the tip, palmar, and lateral pinch would be more suited to small, delicate objects.

In contrast to the generality of Schlesinger's categories, Cutkosky and Wright attempted to codify specifically those grasps used by a machinist. Because a flexible robot will be most valuable in settings similar to a machine shop—factories, automated fabrication facilities, outer space, underwater, etc.—these classifications are of particular interest. Their more specific and numerous grasp types are shown in Figure 2. Although these nine grasp types include five of Schlesinger's, the tip grasp is divided into four categories based on the number of active fingertips, and the power grasp, in which the thumb is used to lock the fingers around an object, is included as well.

Although these representations are a convenient means to describing object/hand relationships, they are unavoidably linked to the human hand model. In order to design an end effector without prejudice towards anthropomorphism, these grasping classifications must be considered more as one possible means to successful object apprehension than as a pattern which must be followed. The *function* of each of these grasps is more important than the specific implementation. For example, the 2-, 3-, 4-, and 5-fingertip grips of Cutkosky and Wright, as well as Schlesinger's tip prehension, are all examples of precision grasps used by humans when they wish to have fine control over object movement, and are usually associated with small objects. But the chuck of a drill, the collet of a lathe, chopsticks, and a quadriplegic's lips can all perform similar functions. Even a human child may prefer Schlesinger's cylindrical grasp over tip prehension when first learning to write. There are necessarily overlaps and ambiguities in any attempt at grasp classification; rather than attempt to exactly duplicate these modes, it is preferable to span their range of function.

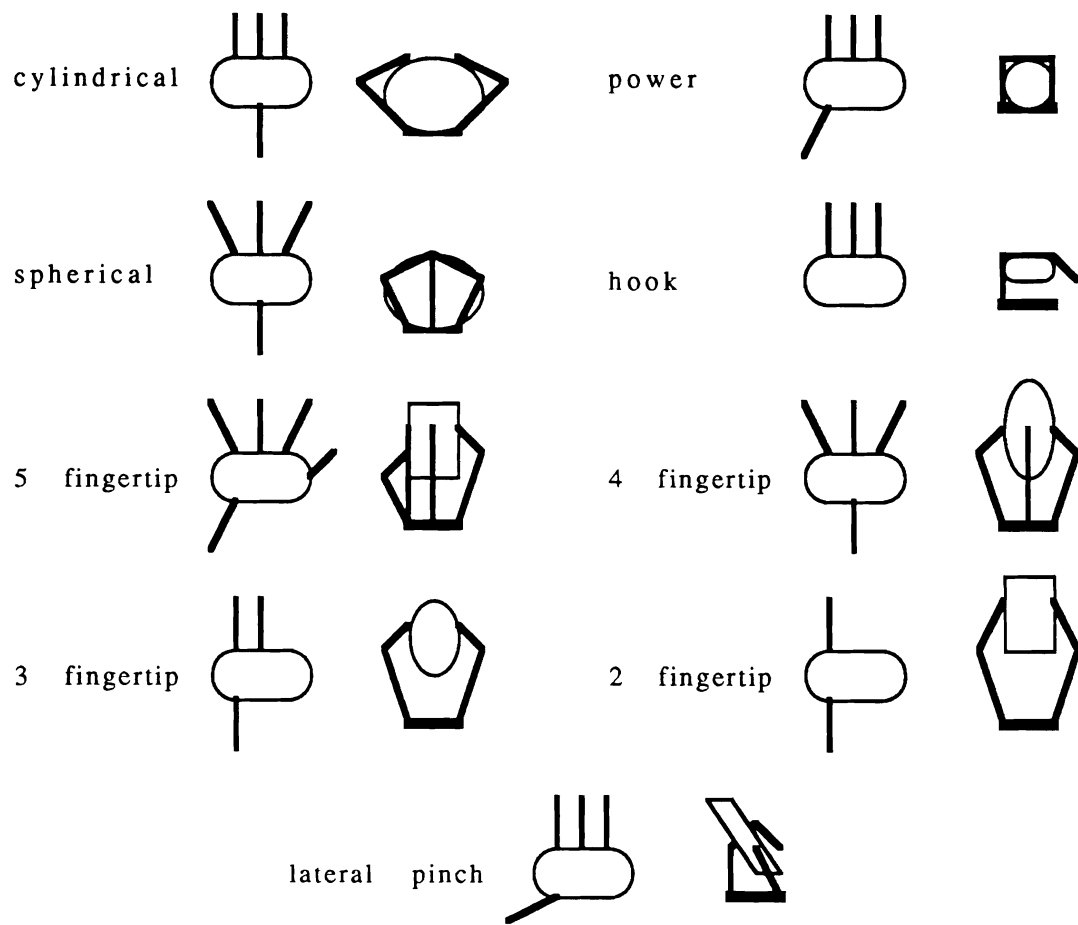


Figure 2: Cutkosky and Wright's manufacturing grips

	Properties	Hand Movements
Surface Properties	Texture Hardness Temperature Weight	Lateral Motion Pressure Static Contact Unsupported Holding
Structural Properties	(Weight) Global Shape Exact Shape Volume	(Unsupported Holding) Enclosure, Contour Following Contour Following Enclosure

Figure 3: Exploratory procedures used by humans

Active Sensing

An end effector can be used for far more than just grasping objects. Because it is one connection between a robot and the world, an end effector can also be used to gain information about its environment. In many cases, such sensing is integral to successful task completion—vision and other *remote sensing* requires the use of such *active sensing* to remove uncertainty. The research of Klatzky and Lederman has shown that human perception is extremely dependent upon physical contact with the world, and that the human vision system is used interdependently with other types of sensing[16, 17, 18, 19].

From their experimental results, Klatzky and Lederman were able to define several *exploratory procedures* (EP’s) which were used by their subjects to obtain information about unknown objects. Figure 3, adapted from [20], shows the properties of an object and the corresponding EP’s used to investigate these features.

Robotics researchers have used similar approaches. Allen used a sensor-covered finger to identify surfaces, cavities, and holes in a visual object image[21]. His work proved conclusively that although vision can give much of the information necessary for an accurate object description, the use of active sensing is absolutely necessary to supplement the visual image. Because remote sensing can easily be fooled—even the sophisticated human visual system—actual physical contact with an object is

necessary. Although the tool he used for his research was crude, simply one rigid finger with a number of tactile sites covering its surface, the amount of information that could be acquired was quite impressive.

Stansfield used the set of exploratory procedures defined by Klatzky and Lederman to attempt to identify and classify objects[22]. Her expert system used active *haptic* exploration, guided by a passive visual system, to learn about the environment, and, in combination with low-level sensing, to recognize generic objects. Her work helped justify the hypothetical connection between human psychological sensing research and artificial intelligence as applied in robotics.

Tsikos used laser range data and a gripper/arm manipulation system to determine the nature of the connections between objects[23, 24]. His work has shown definitively that active sensing, in fact, active manipulation of object attributes, is necessary in order to segment a sensed object into its component pieces. Without the additional information provided by dynamic exploration, a remote sensing system is incapable of determining the nature of the connection between perceived objects; *e.g.*, whether they are rigidly attached or simply resting one upon the other.

The research into active sensing is hampered by ineffective tools. One of the goals of the work presented here is to provide an end effector which will serve as a platform for the sensors necessary to explore objects, as well as a tool for manipulation these objects.

Thesis Outline

The chapters within this thesis show the progression of the design process. In reality, this does not follow strict chronological order; rather, the path which illustrates the elements of the design most clearly and logically was chosen.

This chapter has shown what previous researchers have done in fields related to end effector design. Chapter Two will combine these ideas and some practical

considerations into a concise expression of the design problem and goals. It will also explain the philosophy of the designer. The next two chapters present the solution: Chapter Three is concerned with the palm design, Chapter Four with the finger design. In Chapter Five, an analysis of some aspects of the design is presented, as well as a computer simulation based on the results. A grasp planning algorithm using these tools is also described and its implementation demonstrated. Chapter Six concludes with an evaluation of the success of the design, and discusses areas of future research.

An attempt has been made to emphasize underlying principles rather than a specific implementation. For this reason, the main body of the thesis does not contain precise design details, nor does it discuss mechanical design elements such as bearings, motors, or gears. Instead, Appendix A presents the details of the first version of the UPenn Hand, an end effector specifically for the research laboratory and Appendix B describes the Rotary Breakaway Mechanism, a type of friction clutch invented to actuate the fingers. Finally, Appendix C presents control and sensing systems.

Chapter 2

Design Criteria

Any solution requires a precise definition of the problem, as well as the constraints under which that problem must be solved. An end effector mechanism is no different. Chapter One discussed the previous research important to hand design. This chapter will attempt to clearly define the criteria for a successful design.

For a mechanism as sophisticated as a robotic end effector, there are a wide variety of solutions to any given application. These variances reflect the philosophy of the designer. This chapter will present the design philosophy expressed later in the thesis, and justify several choices made at the outset of the design process.

The design discussed here is meant to be useful in a wide range of applications, from flexible manufacturing to underwater to a research laboratory. The aim is to present the basis for a wide range of *medium-complexity* end effectors, which are strong, robust, self-contained, and easy to control and use. The UPenn Hand, which was specifically designed for a research laboratory, is described in detail in Appendix A.

Goals

From the grasping classifications described in the previous chapter, we can obtain a very specific set of requirements for an end effector. The design will be considered successful if it can achieve the grasping modes of Schlesinger and Cutkowsky and Wright, or, alternatively, can grasp the same types of objects that are represented by these modes. An emphasis on power grasps is preferred to precision grasping.

One practical goal is a self-contained end effector which can be mounted on a conventional robot arm. However, from grasping analysis, the consensus is that nine degrees of freedom (DOF) are necessary for manipulation of an object within a fingertip grasp[1, 9, 25]. While other hands with 9 or more DOF have had the actuators mounted remotely or have used special-purpose arms, neither of these options is ideal. The control of a large number of degrees of freedom is also considered a major problem, since experience in control of complicated systems has shown that computational complexity increases exponentially with the number of degrees of freedom. This is evident from the mathematics used to describe serial manipulators[26]. In order to meet weight and space constraints, as well as to simplify control, a successful design would have fewer than five actuators.

With less than 9 degrees of freedom, it is not possible to arbitrarily position three fingertips in space, which means that object manipulation within a grasp requires interaction with the environment or another hand. However, an emphasis on enveloping grasps for object apprehension—which require fewer degrees of freedom and provide geometrically stable prehension—will extend utility.

Enveloping grasps also give much information about object shape and size. By lifting an object free of support, weight and density can be obtained. But the exploratory procedures of Klatzky and Lederman, as well as the research of Allen and Stansfield, show the need for several other end effector characteristics. One finger should be extensible as a probe. This finger should have tactile, force/moment, and other specialized sensors to allow for discovery of object attributes such as texture,

hardness, and temperature, as well as for contour following. A large surface, such as the palm, should be covered with a tactile array which allows “footprints” of an object. These attributes are quite compatible with other design imperatives, and they allow the determination of object properties which are essential for successful manipulation of unknown objects.

Design Philosophy

In the design of a mechanical hand, it is tempting to try to duplicate the human hand. However, most applications for robotic hands require a small subset of the abilities required of the human hand; it is better to design for the advantages and disadvantages of the tools that are available. There is no reason that a robotic end effector can't be better in some situations than the human hand, in much the same way that automobiles are faster than humans when traveling on smooth roads.

We can, however, learn from the human model. Because a designer has the human hand readily available as a referent, it is unreasonable to avoid using it as a model on some level. There are certain operations that the human hand uses over and over again when grasping and manipulating objects. These *grasping primitives* are a way of reducing the complexity of a grasping operation to a sequence of preprogrammed motions. The human hand performs these on a reflexive level; with concentration, each joint in the human hand can be moved individually, but this is rarely necessary.¹

Rather than implement these grasping primitives at the control level, which means we must have actuation and low-level control for each movement, we define the concept of *mechanical intelligence*. It is possible to imbue a mechanism with the ability to respond and react to the environment without guidance from a controller. By nature, the performance of such a device is predictable and invariant, but in some situations

¹I am indebted to David Brock of MIT's Artificial Intelligence Laboratory for pointing this out. I was previously under the mistaken impression that we could not control the last two finger joints independently. They are apparently coupled as part of the learning process, as well as mechanically.

this is an attractive alternative. In this case, a mechanically intelligent end effector would implement grasping primitives at the mechanical level, as far outboard as possible. There are several advantages to this: it allows for simpler control, it provides for fewer actuators, as well as making the device self-contained, low-maintenance, and reliable.

Throughout the design process, we also attempt to adhere to the principles of good design. Whenever presented with a set of options, choose the one which is simplest, cheapest, and most reliable, all other things being equal. By avoiding exotic options, the design may prove to be less interesting, but it will be much more useful and robust.

In addition, an emphasis was placed on “quick-and-dirty” prototyping; that is, the implementation of design ideas in a form that is easy to test and takes little time to build. In some cases, manually controlled prototypes were built to test ideas without the investment of time and money into computer-control architectures and equipment. One such device is discussed in detail in Chapter Three. Although some computer and mathematical simulation techniques were used (one is discussed in Chapter Five), actual physical implementation was considered necessary to confirm theoretical results.

The overall design philosophy of this hand design is to emphasize practicality, common sense, and ease of use over all else. After all, the resulting end effector is meant to be a tool, in whatever application, and the ideal tool is transparent to the user, whether man or machine.

Chapter 3

The Palm

A hand design can be separated into two parts: the design of the palm and how the fingers relate to each other, and the finger design itself. This chapter will discuss the palm design, the next will present the finger design.

A palm is essentially a junction for a number of serial manipulators. In many hand designs, this is the only function that it serves. But if we look at how the human hand works, we see that the palm is much more than simply where the fingers attach. The palm is used as a platform for grasping, a surface against which objects are held in enveloping grasps. These enclosure grasps, as mentioned in the previous chapter, are especially important for a hand design with limited degrees of freedom. In such a prehension mode, the hand provides one or more “free” contacts, that is, contacts which do not require additional degrees of freedom, and therefore do not require an increase in the number of actuators and the control complexity.

As mentioned previously, the palm can also serve as a sensing medium. With the fingers folded out of the way, the palm can be pressed against objects and a tactile sensing array can be used to obtain information about the object. A tactile footprint can also be obtained by grasping an object in an enclosure grasp. In this case, the contact pressure of the object against the palm can be varied by increasing or decreasing the finger contact forces.

The palm, if well-designed, can serve another function. Mason and others[7, 8] have analyzed the behavior of objects when pushed. The palm is an ideal surface for this, since it is rigidly attached to the end of the robot arm. The contact force in this case is limited only by the strength of the arm, not by the fingers. The fingers can be used to guide the object against the palm, and to change the shape of the “pusher.”

A Class of Junctions for Serial Linkages

A serial mechanical linkage, in general, is a sequence of “screw joints” connected in a series of links, each link being connected to only one other link. In robotics, mechanisms with only translational or rotational joints—special cases of the more general screw joint— are most common. The movement of a link is only dependent on the movement of the links previous to it, and this movement can be explicitly and uniquely defined for each set of the previous joint movements by use of *forward kinematics*. The human arm, a snake’s body, and a backhoe are all examples of serial mechanical linkages.

There has been much research into the behavior of robot arms, fingers, and legs, and the dynamics and kinematics of these mechanisms has been thoroughly studied. However, these linkages are often connected together in some fashion to form hands, walking machines, or multi-arm robot systems. Very little attention has been paid to connections or *junctions* between serial linkages. In order for a combination of linkages to be considered serial, they must be connected only at their base, or zeroth link. The geometry of this connection is what determines the properties of the combined mechanism.

The number of so-called *junctions of serial linkages* is infinite, but one special class of these mechanisms is of particular interest to the work presented here. Because of their suitability for hand designs, this area has been explored extensively, but current work investigates other applications.

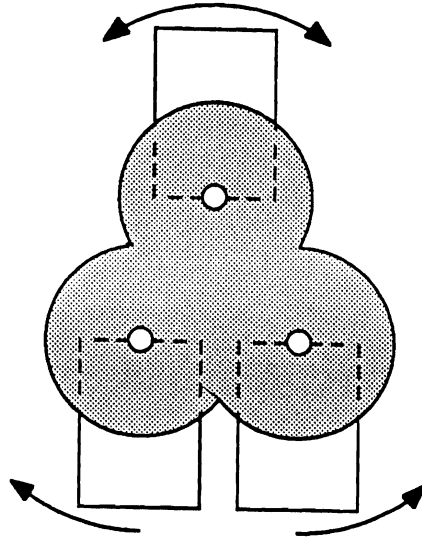


Figure 4: The palm of the Compliant Articulated Mechanical Manipulator

One Special Set

The author originally proposed one type of junction in the Compliant Articulated Mechanical Manipulator (CAMM), a multi-jointed three-fingered mechanical hand[27] (see Figure 4). The palm of CAMM is a specific implementation of a more general class of junctions for serial manipulators.

If we consider n serial linkages which are to be connected at their base, then for each n , we can define this method of linking the base of each linkage. Let us assume that the axes of rotation for the first joint of each of these linkages pass through points equally spaced along a circle of radius d , and that these axes are perpendicular to the plane which contains the circle. We further assume that the first link which contains this first rotational joint has width w and length r . The geometry of this case is shown in Figure 5 for $n = 4$.

The degenerate case is when $d = 0$, and the axes of rotation coincide. In this situation, for non-zero values of w and $n > 1$, the interference between joints limits the rotational range of the linkages. The linkages can never move until they are parallel to each other. However, if we increase d , we increase the maximum angular displacement of each linkage's first joint. One very useful result of this is that we can find an expression for a d which allows a link to be parallel with the links on either

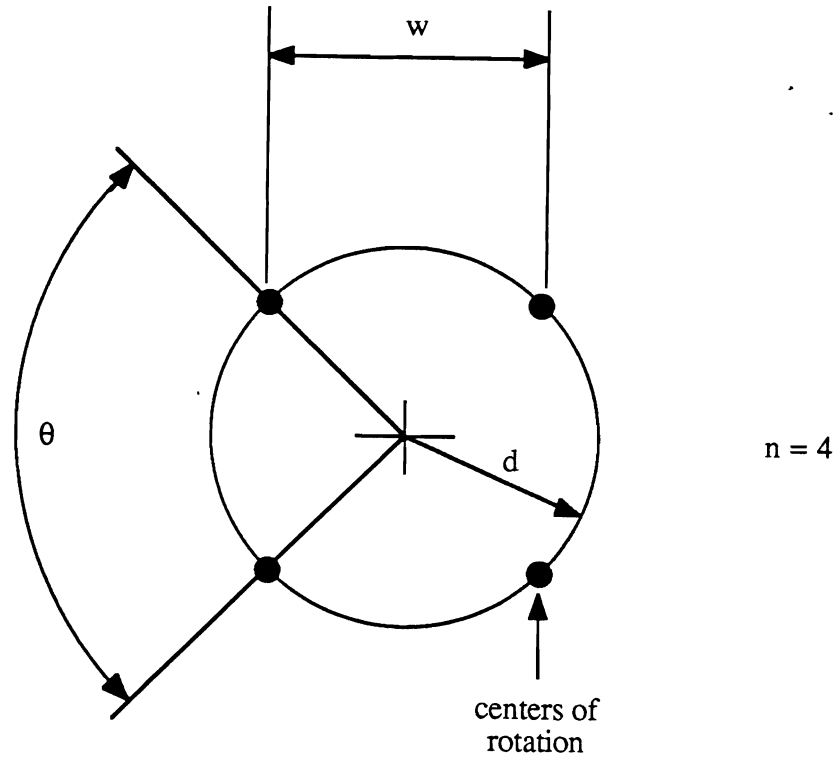


Figure 5: An example with $n = 4$

side of it. In this case,

$$d = \frac{w}{2 \sin(\frac{\theta}{2})}$$

where $\theta = \frac{2\pi}{n}$. If we establish radii of rotation around these separated centers, then we see that the linkages move around lobes of the junction. It is important to note that in this class of junctions, the second joint of the serial linkages is displaced by a radius r from the center of rotation. This separation is what allows such a wide range of movement for the serial linkage. When $r = 0$, we have a degenerate case. Figure 4 shows several simple examples for $n = 1$ to 4.

It is possible to vary the possible junctions widely with the addition of fixed serial junctions between lobes. If $n = 2$ and a fixed finger is placed between the two movable fingers, then we have a configuration which is quite versatile. If we couple the movement of the fingers around the palm, we have a junction with only one degree of freedom, but one that can achieve a very wide range of grasping configurations. Figure 7 shows the five types of grasps possible.

Another advantage to this configuration is that the palmar surfaces of the fingers

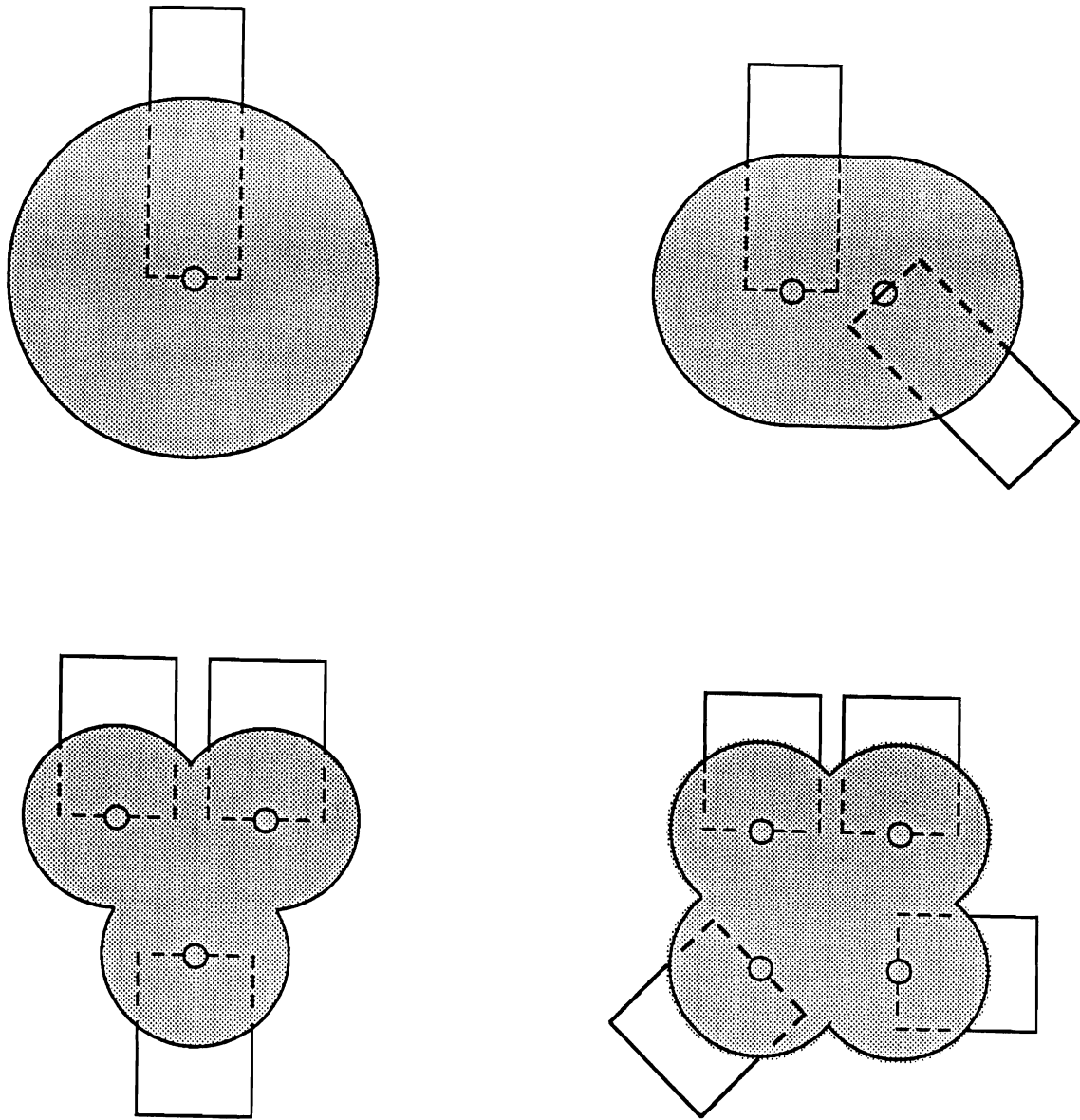


Figure 6: Several possible junctions for serial manipulators

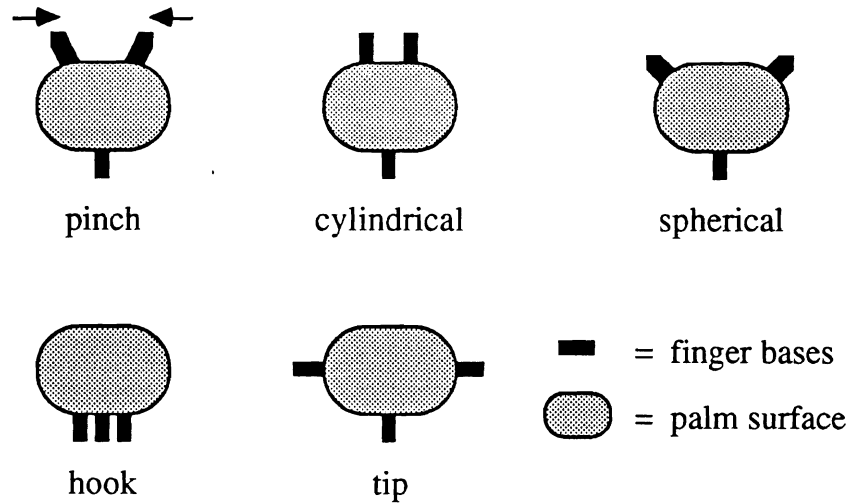


Figure 7: Five grasping modes

are always facing directly inwards—simplifying the sensing of an object within a grasp—in contrast to the human hand, where the lateral movement of the fingers does not allow this. The five grasping modes are described below with their parallels in Schlesinger’s and Cutkosky and Wright’s work defined as well:

The **pinch** grip occurs when the two movable fingers are brought together on the opposite side of the palm from the thumb. The inside of these two fingers are lined with rubber, which allows for friction grasping of small objects. This is primarily a precision grasp, used for picking up small, delicate objects. It is similar to the lateral pinch grasp described by both Schlesinger and Cutkosky and Wright. In addition, some operations which are usually performed by Schlesinger’s tip prehension and Cutkosky and Wright’s two-finger precision grasp can be achieved in this configuration. The flexibility of this grasp is enhanced by the ability to change its nature by changing the angle of the fingers. In Figure 8, this technique is illustrated. This grasp is very similar to the precision grasp used by amputees who have been fitted with a split hook prosthesis. In this case, a cylindrical groove between the halves of the hook allow for stable grasping of a pencil or similar small cylindrical objects.

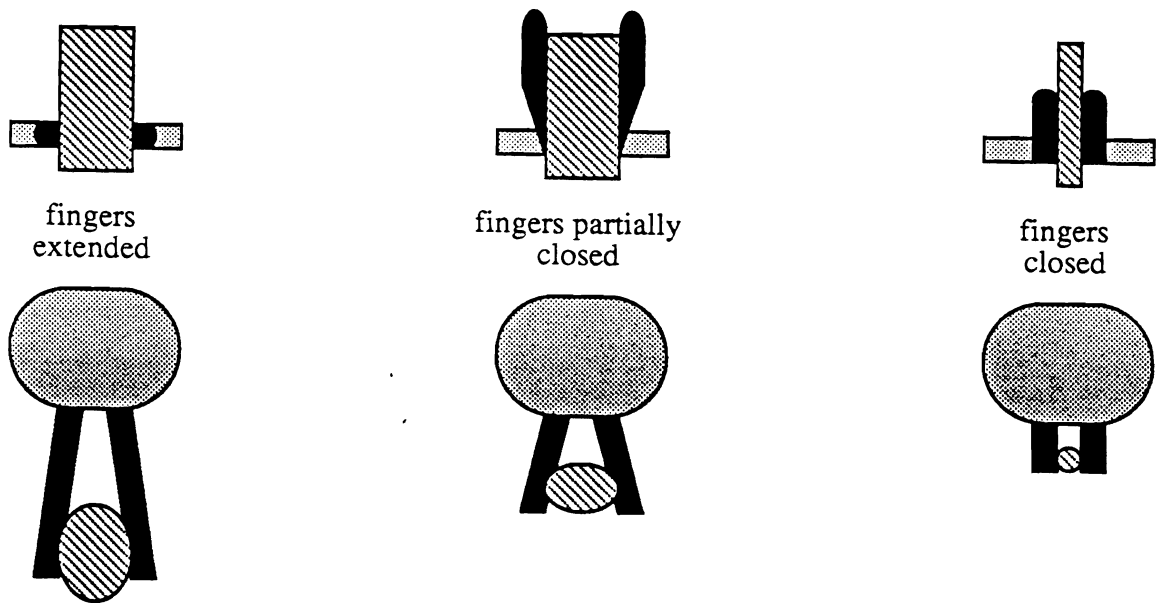


Figure 8: Variations of the pinch grasping mode

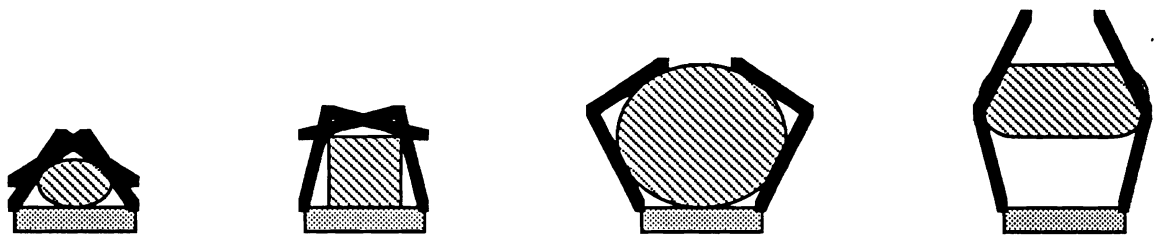


Figure 9: Variations in the cylindrical grasping mode

Such an implementation in the robotic end effector could prove useful.

The **cylindrical** grasp, when the two fingers are opposite the thumb, is analogous to Schlesinger's cylindrical grasp and Cutkosky and Wright's cylindrical power and precision grips. This mode allows for the apprehension of a wide range of shapes and sizes, from small cylindrical objects to larger rectangular box-shaped objects (see Figure 9). In addition, this mode allows a version of the lateral pinch grasp, when an object is held between the three fingertips. The attractiveness of this grasp lies in its strength. Since the palmar surfaces of all three fingers are holding the object against the palm, objects are held very securely.

The **spherical** grasp, with the three fingers roughly 120 degrees apart, is similar to Schlesinger's spherical grasp and Cutkosky and Wright's spherical power and 3-finger, 4-finger, and 5-finger precision grasps. In a power grasp, the palmar surfaces of

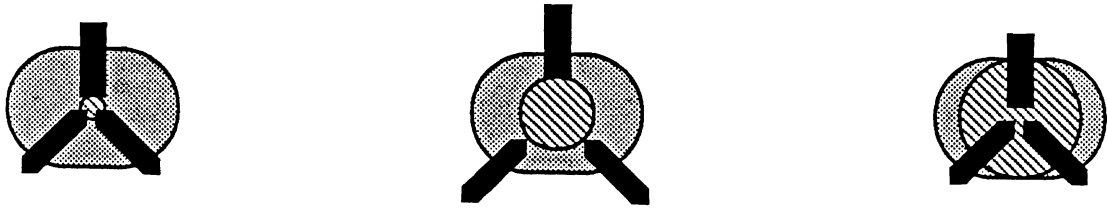


Figure 10: Variations of the spherical grasp



Figure 11: Variations of the hook grasp

the fingers are used to hold a spherical object against the palm, while in a precision grip, the three fingertips form a three-sided fingertip grasp which is similar to the chuck on a drill. In Figure 10, the application of this grasp to various objects is shown.

When the two fingers are rotated until they are opposite each other, they can be used in a **tip** grasping mode. This is exactly the tip prehension described by Schlesinger and the 2-finger precision grip described by Cutkosky and Wright. Although this grasp relies primarily on friction for stability, it can be useful in apprehending objects that are awkwardly placed or for manipulating objects securely held in some manner. The pinch grasp provides a more stable grasp of most small objects.

The **hook** mode of grasping uses all three fingers located together on one side of the palm. This allows for two types of grasping: a passive grip on a handle or similar structure where the fingers act as a hook, or an active grasp where all three fingers hold a large object against the palm. This is a grasp that could be used to lift one side of a large flat object (in cooperation with another hand) where the size of the object precludes an enveloping grasp. Figure 11 shows these uses.

Experimentation

To test the performance of such a palm/finger relationship, a crude teleoperated prototype of the hand was built. Rather than invest a great deal of time and money into developing a computer-controlled prototype, this simple device, machined from aluminum, has three single-jointed fingers which are actuated by means of stainless-steel cable. A grip which fits the human hand allows the experimenter to control the fingers and the movement of the fingers around the palm. The current implementation has flexible sheaths which allow the hand itself to be moved independently of the control grip.

In order to effectively test the abilities of such a mechanism, a small internal-combustion engine was chosen as a typical disassembly subject¹ Using standard tools, such as screwdrivers and wrenches, the hand was used to partially disassemble the engine. This experiment, along with other, more specific, analyses of each grasp, allowed a precise determination of the abilities and weaknesses of the palm geometry. From these results the thickness of the fingers relative to the palm, the actual palm shape, and the optimum movement of the fingers relative to each other was determined.

It is surprising that a mechanism with such a limited number of degrees of freedom—especially in this poor implementation—could perform such a complicated task. All of the credit for this success cannot go to the design. In this case, a human arm replaced a robot arm, the human brain replaced a control computer, and human muscles replaced actuators; these components greatly increased the ability of the mechanism. However, only the palm/finger geometry was being tested in this experiment; no claims as to the eventual performance of a computer-controlled prototype are made based on these experiments.

This configuration was found suitable and adopted in the design of the first version

¹This at the suggestion of Dr. Richard Paul, who felt the usefulness of the hand could be tested best manually and in a real application.

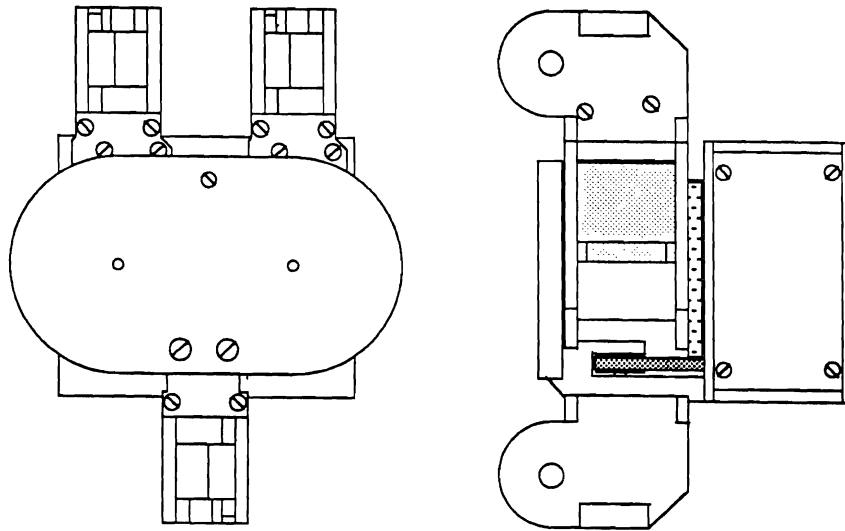


Figure 12: Assembly of palm and finger bases in the UPenn Hand

of the UPenn Hand. Figure 12 shows an assembly drawing of the palm and finger bases.

Although the palm/finger relationship seemed close to optimum, there were significant problems with the fingers. It was found that fingers with only a single joint have serious difficulties in wrapping around objects and obtaining the enveloping-type grasps discussed in Chapter Two. Although various finger shapes were tried, each was found to be optimal for only a limited number of objects. And although it was possible to use the fingertips in friction-type grasping, the stability was variable and relied upon a rubber coating for the fingers. The next chapter will present an alternative approach to the finger design.

Chapter 4

The Finger

The previous chapter defined a type of palm/finger relationship with one degree of freedom. Although five distinct grasp modes are obtained with this configuration, a finger design which is useful in all of these modes is necessary for the best performance. Optimally, each finger would use only one actuator, which would give a total of four actuators for the complete hand.

However, based on the experimentation described earlier, it seems that single-jointed fingers have limited usefulness. At least two joints are necessary to achieve the preferred enveloping grasps, and in order to obtain the number of contacts necessary for stable frictionless grasping. One option would be to switch actuation from joint to joint by means of clutches, brakes, or solenoids, and let the controller decide the relative motion of each finger joint. But, in keeping with the design philosophy expressed in Chapter Two, it is preferable to look for a mechanical solution.

Coupled Joints

The author originally proposed the concept of *coupled joints* in his Compliant Articulated Mechanical Manipulator, which used two motors per finger to actuate four tendon-driven joints[27]. Leaver based a later three-jointed two-actuator finger design

on this idea, and also proposed a matrix method of representing such coupling[28].

These designs used tendons to transmit torque from the actuator to the joints. By varying the tendon routing and the size of the pulleys used, various coupled motions can be produced. Joints can be driven by other joints in a similar manner.

The advantage of coupled joints is that fingers can be designed so as to more easily conform to the shape of objects. This is extremely useful in enveloping grasps, where stability depends on contacts on the palmar surfaces of the fingers, that is, on the inside surfaces of joints instead of just the fingertips. Such grasps are stronger and more stable since they do not rely on friction for stability[11]. However, rigid coupling between joints defines a single set of joint angles for each actuator displacement. For example, if two joints are coupled by pulleys with radii of r_1 and r_2 , the joint displacements θ_1 and θ_2 are defined by the relation:

$$\frac{\theta_1}{r_1} = \frac{\theta_2}{r_2}$$

Such rigid coupling means that contact on both joints will occur only for a small set of convex objects—most objects will only contact the finger on only one joint. However, if we place a spring or rubber section in the coupling tendon the finger will wrap around an object and insure multiple contacts. This design is compliant only in closing, and in most cases can exert large contact forces; a description of such a finger can be found in [29].

Neither of these implementations is ideal. Rigid coupling does not fully utilize the advantages of coupled joints, and compliant tendons can adversely affect grasp stability in certain cases.

A Two-Jointed Compliantly Coupled Finger

A new transmission and actuation method for coupled joints is shown in Figure 13. Two worm gears are connected to the finger actuator. One worm wheel is rigidly attached to the first joint of the finger, the other is attached to a pulley. Stainless-steel

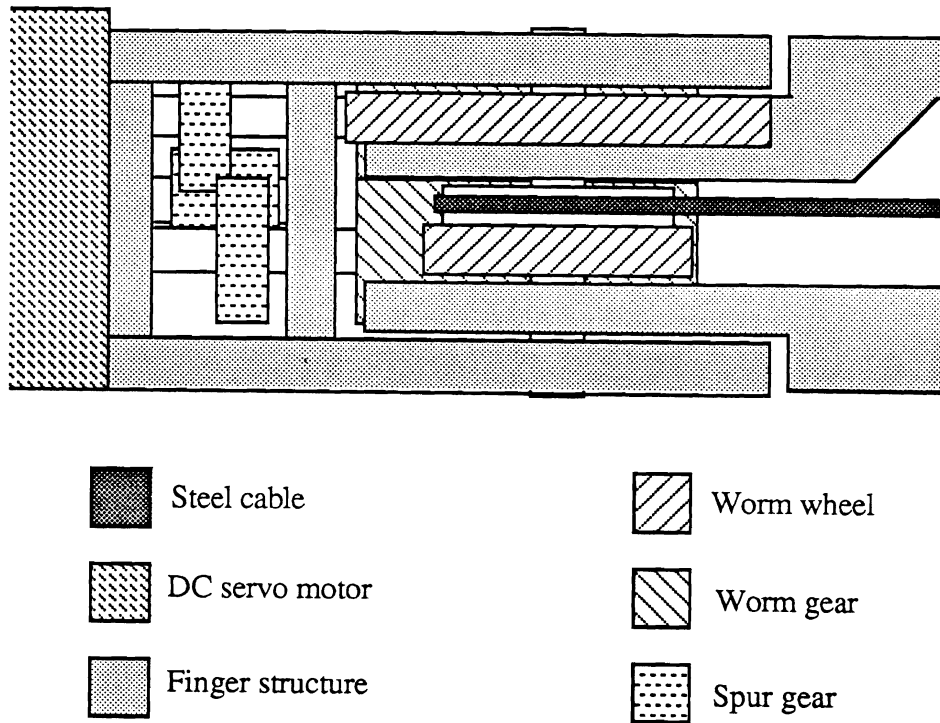


Figure 13: Actuation of Coupled Joints

cable connects this pulley to another at the second joint. In the current implementation, a novel “breakaway” mechanism allows for compliance. This mechanism is integral to the worm gear reduction, acts as a clutch which stops movement of the first joint at a certain threshold torque, and has a memory which causes the joints to always return to the same relative position when fully open.

Function

When there is no contact between the finger and the object, the joints will move in a relationship defined by the relative worm gear reductions. When the first joint requires a joint torque higher than the breakaway torque, it decouples from the finger actuator (it will still passively maintain this breakaway torque because of the non-backdrivable worm gear reduction). The second joint will remain coupled to the finger actuator and continue to rotate. If the object shifts within the grasp and the first joint torque falls below the breakaway torque, the first joint will re-couple with the motor and move until the breakaway torque is encountered again.

Two advantages of this design are evident. First, multiple finger/object contacts will result with most objects. Second, after breakaway, the torque around the second joint can be actively controlled. Before breakaway (and in rigidly coupled finger joints), the joint torques are indeterminate, and can be related only by the single equation

$$\frac{\tau_1}{G_1} + \frac{\tau_2}{G_2} = \tau_{motor}$$

where τ_1 and τ_2 represent the torques at joints 1 and 2, G_1 and G_2 represent the gear reductions for joints 1 and 2, and τ_{motor} represents the torque provided by the joint actuator. After breakaway, the torques are defined by the equations:

$$\tau_1 = \tau_{break} \quad \tau_2 = G_2 \left[\tau_{motor} - \frac{\tau_{break}}{G_1} \right] \quad (1)$$

Now, the torque around the first joint is constant, and any variation in actuator torque will cause a corresponding variation in joint two torque. This allows τ_2 —and the joint two contact force—to be actively controlled, which is the ideal situation to insure grasp stability.

The breakaway torque is proportional to the motor torque on the fingers when they are fully opened against their stops, and can be changed before each grasp. This is useful if the same hand is to be used to pick up both eggs and hammers.

One result of the use of a non-backdrivable worm gear reduction is that large contact forces can be passively resisted to the limit of the strength of the materials used in construction. The use of enveloping grasps allows such a hand to pick up heavy objects which tend to produce high joint torques. In similar situations, a backdrivable gear reduction would require much larger motors.

Because the motors can be smaller and lighter, they are mounted at the finger base. The motor shaft directly drives the two worm gears, and as a result, there is very little backlash in the system. Unlike conventional tendon-driven fingers, which require long tendon runs and complicated pretensioning systems, this design allows for an accurate servo control loop to be closed around the motor—there is minimal error in the

transmission. However, although the joint positions are read by potentiometers at the joints, these displacements are not strictly defined with respect to motor displacement and cannot be actively controlled. Rather, although a function of the two joint positions defines the motor position, there is an infinite range of joint displacements for each motor position, and the joint displacement depends on the shape of the object being grasped.

The non-backdrivable worm gear reduction is not without drawbacks. First of all, although compact, the efficiency of this type of transmission is low. Theoretical values on the order of sixty-five percent are obtained in this application. This varies a great deal depending on lubrication, worm lead, and gear materials. Also, the reaction forces at the supports of the worm wheel and the worm must also be taken into consideration and compensated for in the design of the transmission. And force control of low-efficiency linkages, though a subject of some successful research, is generally considered quite difficult. However, in this specific application, it was found that these trade-offs were acceptable. Further, it proved impossible to achieve the design goals through any other approach.

Mounting the motors at the finger bases allows for all four motors to be placed under the palm. Sensor and power cables are terminated by connectors also located under the palm. The result is a self-contained unit which can be quickly attached or removed from the robot arm and the control system. This is important in situations where multiple end effectors are used on one arm, when repairs have to be made to the device, or when one end effector is to be used on different arms.

The use of the breakaway mechanism in the actuation of coupled joints leads to a near optimal performance for a two-jointed finger. After breakaway, actuator torque is transferred to the second joint, with its shorter moment arm, and (usually) more advantageous contact position. In addition, the compliance provided by this actuation method means that the fingers will achieve enveloping grasps on almost all objects. Figure 14 shows the finger assembly as implemented in the UPenn Hand. The next

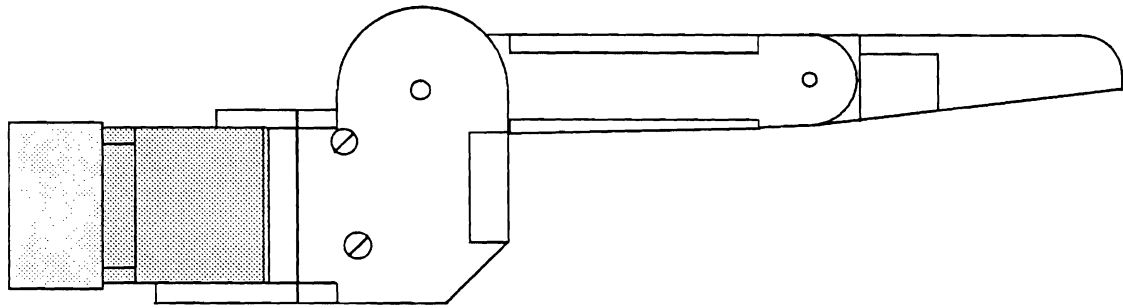
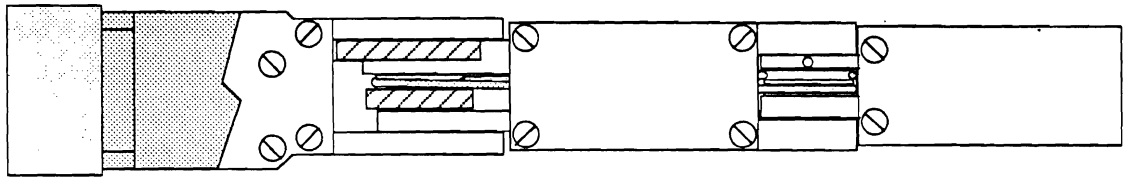


Figure 14: Assembly of the fingers of the UPenn Hand

chapter demonstrates the advantages of this design through analytical methods.

Chapter 5

Analysis

The previous two chapters described the end effector design. In this chapter, analyses of selected aspects of the mechanism are presented in order to show its theoretical behavior. Rather than indulge in a lengthy exposition of all calculations made in the design of the hand, those derivations are shown which illustrate the performance of the hand most clearly, and which are crucial to a justification of the design. These include a kinematic analysis of the fingers relative to the palm, a static analysis of two fingers and a palm in the plane, and a computer simulation of the hand. A grasp planning algorithm is also presented, and its implementation in simulation shown.

Throughout, boldface letters are used to indicate vector or matrix quantities, and non-boldface letters are used to indicate scalar quantities. All other terms and conventions are defined at their first use. Much of this chapter is taken from a previous publication by the author[30], with some modification.

Kinematic Analysis

The position of any point in the reference frame of joints 1 or 2 can be expressed in the reference frame of the palm quite easily using homogeneous transformation matrices[26]. In Figure 15, two points **a** and **b** are shown with coordinates expressed

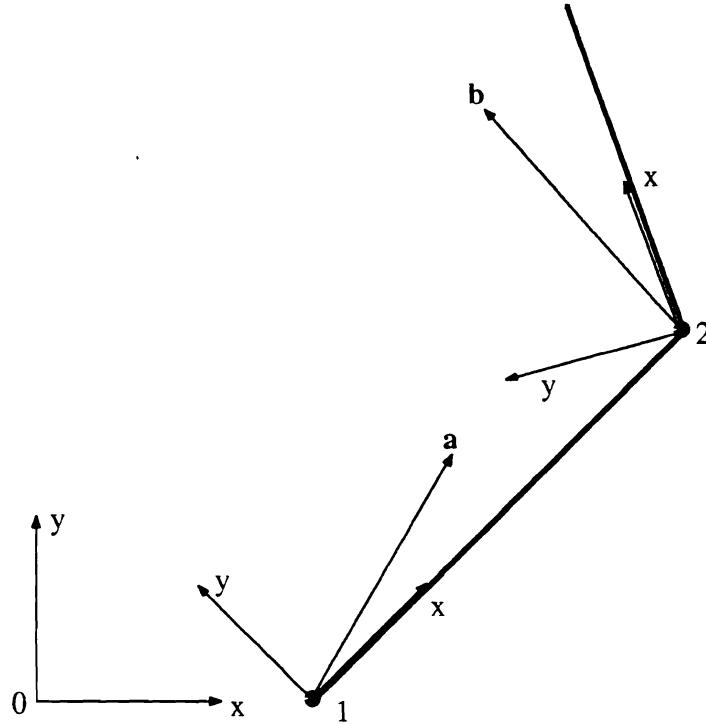


Figure 15: Forward Kinematics of a Finger with Two Parallel Joints

in the reference frames of joints 1 and 2, respectively. If the superscript ⁰ is used to indicate resolution in the reference frame of the palm, then

$$\mathbf{a}^0 = \mathbf{T}_1^0 \mathbf{a}^1 \quad \mathbf{b}^0 = \mathbf{T}_1^0 \mathbf{T}_2^1 \mathbf{b}^2 = \mathbf{T}_2^0 \mathbf{b}^2$$

where \mathbf{T}_j^i is the transformation matrix relating a point expressed in frame \mathbf{j} to frame \mathbf{i} (joint 1 coordinates are frame 1; joint 2 coordinates are frame 2). These equations allow us to find the global position of any point expressed in joint coordinates, given the sensed joint angles θ_1 and θ_2 and the geometry of the finger. Similar equations extended to the three-space of planar wrenches aid us in the following static analysis of contact forces and joint torques.¹

¹The inverse kinematics (finding the joint angles given the global position of a point fixed in the finger) are of no use; the compliant coupling described in the previous chapter does not allow us to arbitrarily determine both joint angles.

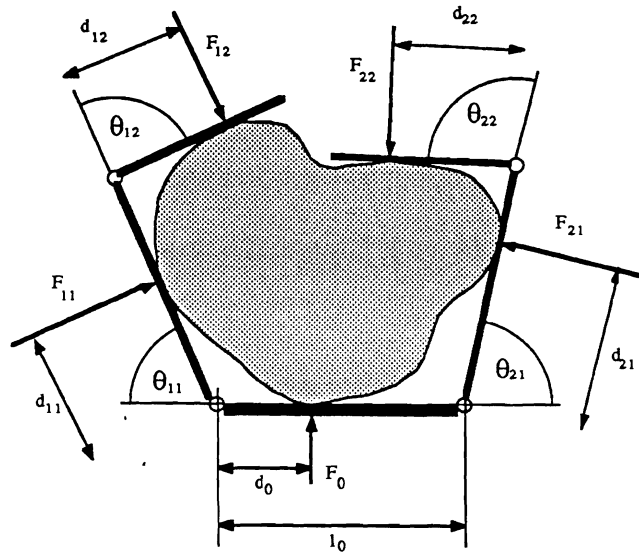


Figure 16: Two fingers and a palm grasping an object

Static Analysis

A static analysis of one isolated finger will not prove instructive. However, if we connect the bases of two fingers by a palm, we can consider enveloping grasps of planar objects. This is a modification of an idea used by Trinkle in analyzing enveloping grasps of planar objects using single-jointed straight fingers[11]. Figure 16 shows a typical case of such a system holding an object. In general, if there are n frictionless point contacts[1] between an object and the hand, the condition for static equilibrium is that[25]:

$$\mathbf{W}\mathbf{c} = \mathbf{W}_{\text{ext}} \quad (2)$$

where \mathbf{W} is the $3 \times n$ matrix of the planar contact wrenches, \mathbf{c} is the $1 \times n$ matrix of wrench intensities, and \mathbf{W}_{ext} is the external wrench being applied to the object (forces and moments exerted by gravity or the environment). The matrix \mathbf{c} can be decomposed into a particular and a homogeneous matrix, such that:

$$\mathbf{c} = \mathbf{c}_p + \lambda \mathbf{c}_h \quad (3)$$

The homogeneous solution \mathbf{c}_h can be found by solving Equation 2 for a \mathbf{W}_{ext} of zero magnitude. The particular solution \mathbf{c}_p will then vary with the value of \mathbf{W}_{ext} . If there exists a homogeneous solution such that all the components of \mathbf{c}_h are positive, then we can find a value of the real constant λ such that the sign of all of the components

of \mathbf{c} are positive. This is useful in the case when we have unisense contact forces; *i.e.* forces which can push but not pull.

A majority of operations that need to be performed by dextrous robot hands require that the grasped object be completely constrained by the hand. Such a situation has been called *form closure*[10, 31]. In other words, the grasping forces may be combined to resist any external wrench on the object. As opposed to that, *force closure* characterizes a situation in which the object is in equilibrium only because the load wrench acting on the object belongs to the union of the non-negative span of the unisense contact wrenches and the span of the other contact wrenches. For example, a human hand tightly grasping a baseball is form closure, where the geometry of the palm and fingers physically prevents the ball from moving, while a coat hanging on a hook is force closure, where stability depends on an external wrench, in this case the weight of the coat. Clearly, form closure is a more stringent condition than force closure.

In this paper, we define grasp stability as form closure in two dimensions. The hand must be able to resist any zero pitch wrench² in the plane of the fingers. In other words, the contact wrenches should span the fifth special three-system[32] that consists of screws of zero pitch along all lines in the plane and screws of infinite pitch along all lines perpendicular to the plane. In practice, however, a more rigorous definition for grasp stability which incorporates the constraints arising from the contact interactions (for example, the frictional constraints) must be used. Here, a geometric definition of grasp stability which is equivalent to form closure in two dimensions is felt to be adequate.

For our analysis, we make several simplifications:

- The contacts between object and finger or palm are considered frictionless point contacts. A line contact is modelled as a single frictionless point contact at the midpoint of the contact segment.

²See [32] for an understanding of screw theory.

- Each finger link (and the palm) has only one contact point.
- The fingers function in the manner discussed in the previous chapter.
- We know the point of contact from tactile sensors or from knowledge of the size and shape of the object. We know the torques (after breakaway) by reference to Equation 1.

It is important to note that these are conservative assumptions; a pessimistic analysis will insure stability when the results are used in real-world situations. Each of these conditions reduce the number of solutions which will give us form closure. Frictional forces are reaction forces and can only resist the movement of an object away from stability. Frictionless point contacts can only exert forces along the contact normal, and in the case of finger/object contact, only with positive sense. But line contacts can also exert moments on a object, so a line contact will improve stability over a point contact. Multiple contacts on a given link will happen with only very irregularly-shaped objects; however, it can be shown that, in general, multiple contacts will produce the same conditions for stability as a single contact[11]. Form closure in this idealized case is a sufficient, but not necessary, condition for form closure with friction, line or multiple contacts.

Next, we solve for \mathbf{c}_h in the equation:

$$\mathbf{W}\mathbf{c}_h = \mathbf{0} \tag{4}$$

In our case, the contacts between the fingers and the object are defined as shown in Figure 16. We can then specify \mathbf{W} and \mathbf{c} , which yields:

$$\begin{bmatrix} \mathbf{W}_{11} & \mathbf{W}_{12} & \mathbf{W}_{21} & \mathbf{W}_{22} & \mathbf{W}_0 \end{bmatrix} \begin{bmatrix} F_{11} \\ F_{12} \\ F_{21} \\ F_{22} \\ F_0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

In the planar case, a wrench can be expressed as:

$$\mathbf{W} = \begin{bmatrix} F_x \\ F_y \\ M \end{bmatrix} \quad (5)$$

If we express all wrenches in a reference frame with an origin at the joint between the palm and finger 1, we obtain:

$$\begin{bmatrix} 0 & s_{11} & s_{1s} & -s_{21} & -s_{2s} \\ 1 & c_{11} & c_{1s} & c_{21} & c_{2s} \\ d_0 & d_{11} & d_{12} + l_1 c_{12} & d_{21} + l_0 c_{21} & d_{22} + l_1 c_{22} + l_0 c_{2s} \end{bmatrix} \begin{bmatrix} F_0 \\ F_{11} \\ F_{12} \\ F_{21} \\ F_{22} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

where s_{ij} is short for $\sin \theta_{ij}$, s_{1s} represents $\sin(\theta_{i1} + \theta_{i2})$, and the distances are as shown in Figure 16.

From the functional description of the finger, we can determine two of the components of the matrix \mathbf{c} : the magnitudes of the forces F_{11} and F_{21} . Assuming breakaway, which we can always obtain by increasing the motor torque,

$$F_{11} \geq \frac{\tau_{break,1}}{d_{11}} \quad F_{21} \geq \frac{\tau_{break,2}}{d_{21}}$$

where $\tau_{break,i}$ refers to the breakaway torque of finger i . To find the homogenous solution, we use the equality in these two expressions and reduce:

$$\begin{bmatrix} 0 & s_{1s} & -s_{2s} \\ 1 & c_{1s} & c_{2s} \\ d_0 & d_{12} + l_1 c_{12} & d_{22} + l_1 c_{22} + l_0 c_{2s} \end{bmatrix} \begin{bmatrix} F_0 \\ F_{12} \\ F_{22} \end{bmatrix} = \begin{bmatrix} F_{11} s_{11} - F_{21} s_{21} \\ F_{11} c_{11} + F_{21} c_{21} \\ F_{11} d_{11} + F_{21} (d_{21} + l_0 c_{21}) \end{bmatrix}$$

The above equation fits the general form of a linear system of equations, $\mathbf{Ax} = \mathbf{b}$, and can be easily solved by premultiplying each side by \mathbf{A}^{-1} . The expression then

reduces to:

$$\mathbf{x} = \begin{bmatrix} F_0 \\ F_{12} \\ F_{22} \end{bmatrix} = \mathbf{A}^{-1}\mathbf{b} \quad (6)$$

where

$$\mathbf{A} = \begin{bmatrix} 0 & s_{1s} & -s_{2s} \\ 1 & c_{1s} & c_{2s} \\ d_0 & d_{12} + l_1 c_{12} & d_{22} + l_1 c_{22} + l_0 c_{2s} \end{bmatrix}$$

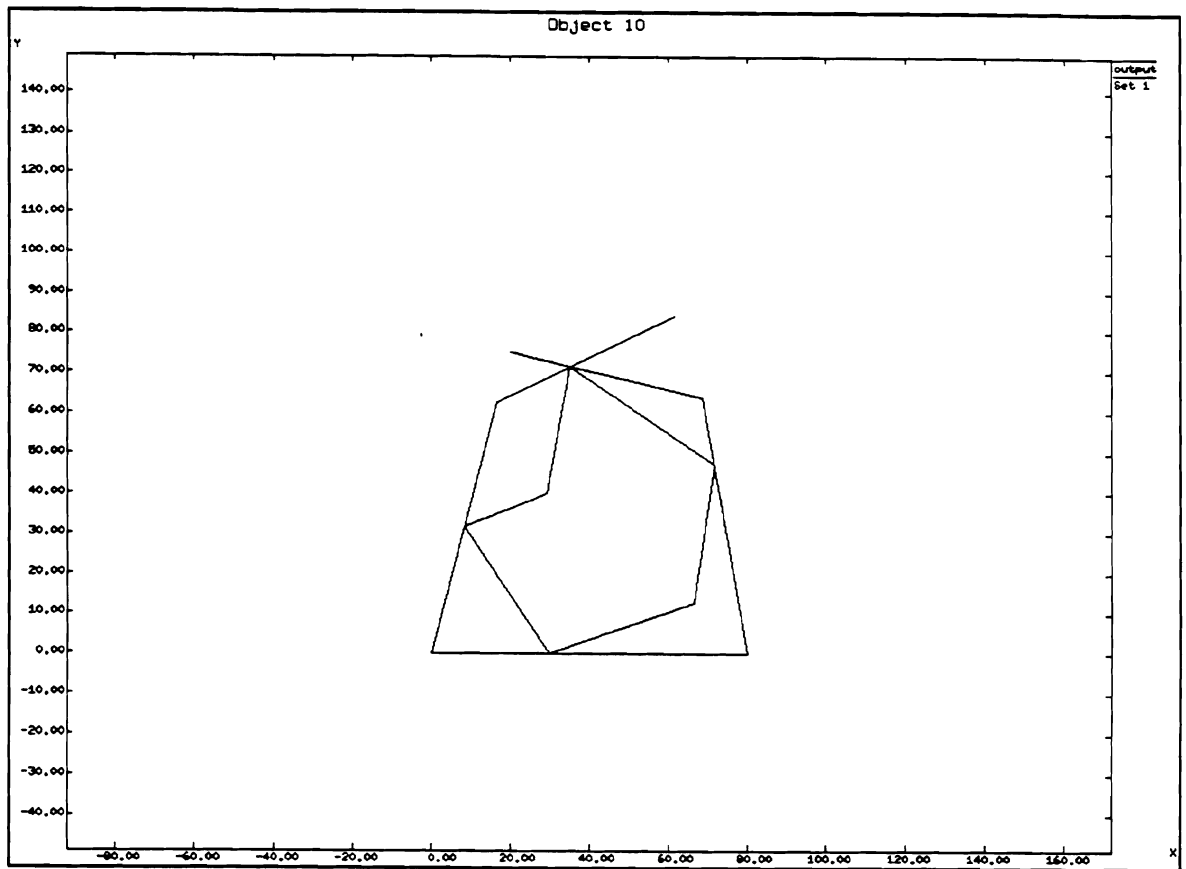
and

$$\mathbf{b} = \begin{bmatrix} F_{11}s_{11} - F_{21}s_{21} \\ F_{11}c_{11} + F_{21}c_{21} \\ F_{11}d_{11} + F_{21}(d_{21} + l_0 c_{21}) \end{bmatrix}$$

Computer Simulation of Planar Grasping

This closed-form solution lends itself to computer implementation. By using a computer simulation of planar grasping, the conditions for form closure can be shown graphically. The first version of the simulator has output of the form shown in Figures 17, 18 and 19. The graph shows the final position of the object with the hand. The data below shows the numerical values of the distances, angles, and forces, as represented in Figure 16; as well as the \mathbf{A} , \mathbf{A}^{-1} , \mathbf{x} , and \mathbf{b} matrices defined in Equation 6. The input is in the form of a number of coordinate pairs representing the vertices of a polygon. Smooth surfaces and curves are approximated by closely-spaced points. The program will rotate the object a specified number of degrees, center it in the grasp, and close each joint of the two fingers until contact is made. The forces F_0 , F_{12} , and F_{22} are then computed using Equation 6. If these forces are positive, then form closure can be obtained simply by increasing the motor torque until the object is completely constrained.

There are several situations where the program will reject the grasp. First, if



Based on breakaway at 0.1 N-m: $f_{11} = 3.0629 \text{ N}$
 $f_{21} = 2.0786 \text{ N}$

$d_0 = 30.0 \text{ mm}$ $\theta_{a11} = 104.8 \text{ deg}$
 $d_{11} = 32.6 \text{ mm}$ $\theta_{a12} = 49.8 \text{ deg}$
 $d_{12} = 20.6 \text{ mm}$ $\theta_{a21} = 100.0 \text{ deg}$
 $d_{21} = 48.1 \text{ mm}$ $\theta_{a22} = 67.1 \text{ deg}$
 $d_{22} = 34.4 \text{ mm}$

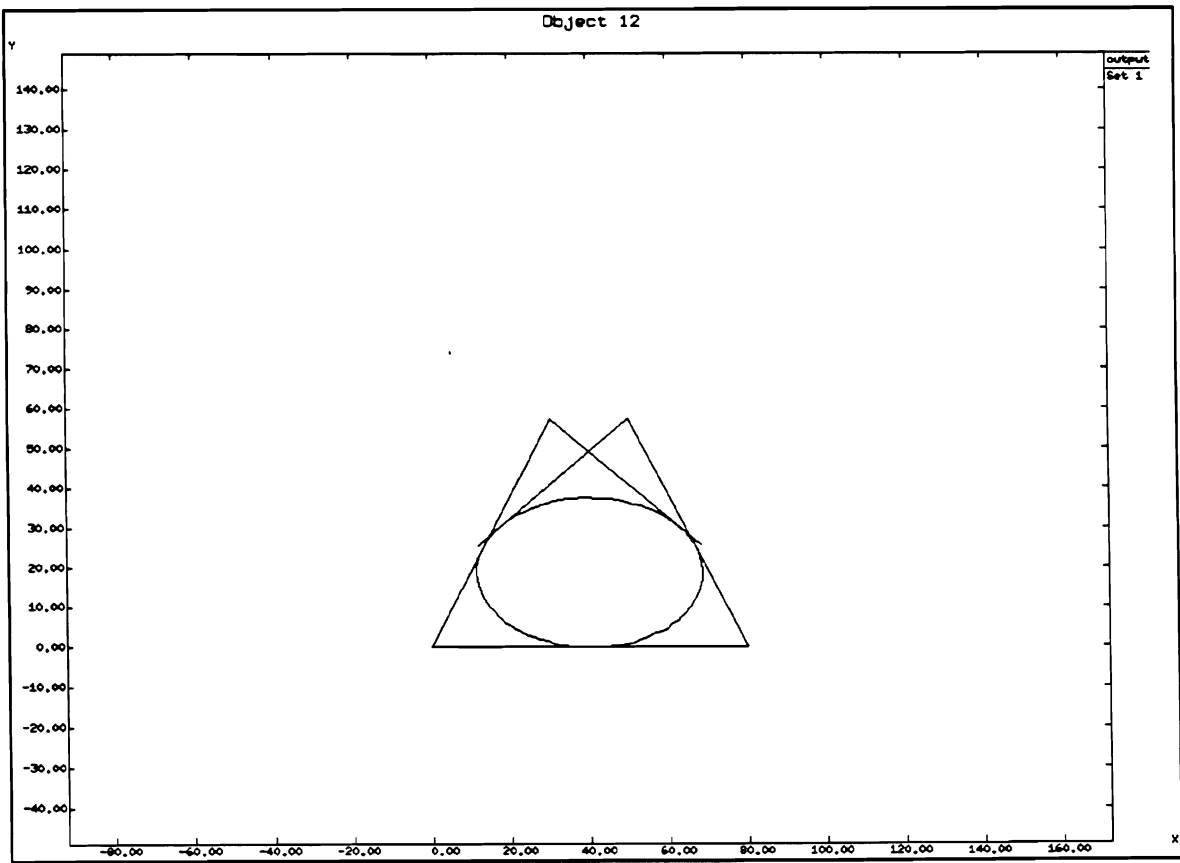
$A = \begin{bmatrix} 0.0000 & 0.4290 & -0.2231 \\ 1.0000 & -0.9033 & -0.9748 \\ 29.9826 & 62.5648 & -18.3268 \end{bmatrix}$

$\det(A) = -24.6806$

$f_0 = 1.1445 \text{ N}$ -1 -3.1418 0.2471 0.0251 0.9143
 $f_{12} = 2.2611 \text{ N}$ $A =$ 0.4416 -0.2711 0.0090 $b =$ -1.1416
 $f_{22} = 0.2499 \text{ N}$ -3.6323 -0.5212 0.0174 171.2010

This grasp is stable.

Figure 17: Grasping a Five-Sided Polygon



Based on breakaway at 0.1 N-m: $f_{11} = 3.3054 \text{ N}$
 $f_{21} = 3.5067 \text{ N}$

$d_0 = 40.0 \text{ mm}$ $\theta_{a11} = 117.8 \text{ deg}$
 $d_{11} = 30.3 \text{ mm}$ $\theta_{a12} = 102.1 \text{ deg}$
 $d_{12} = 44.0 \text{ mm}$ $\theta_{a21} = 117.3 \text{ deg}$
 $d_{21} = 28.5 \text{ mm}$ $\theta_{a22} = 102.8 \text{ deg}$
 $d_{22} = 44.4 \text{ mm}$

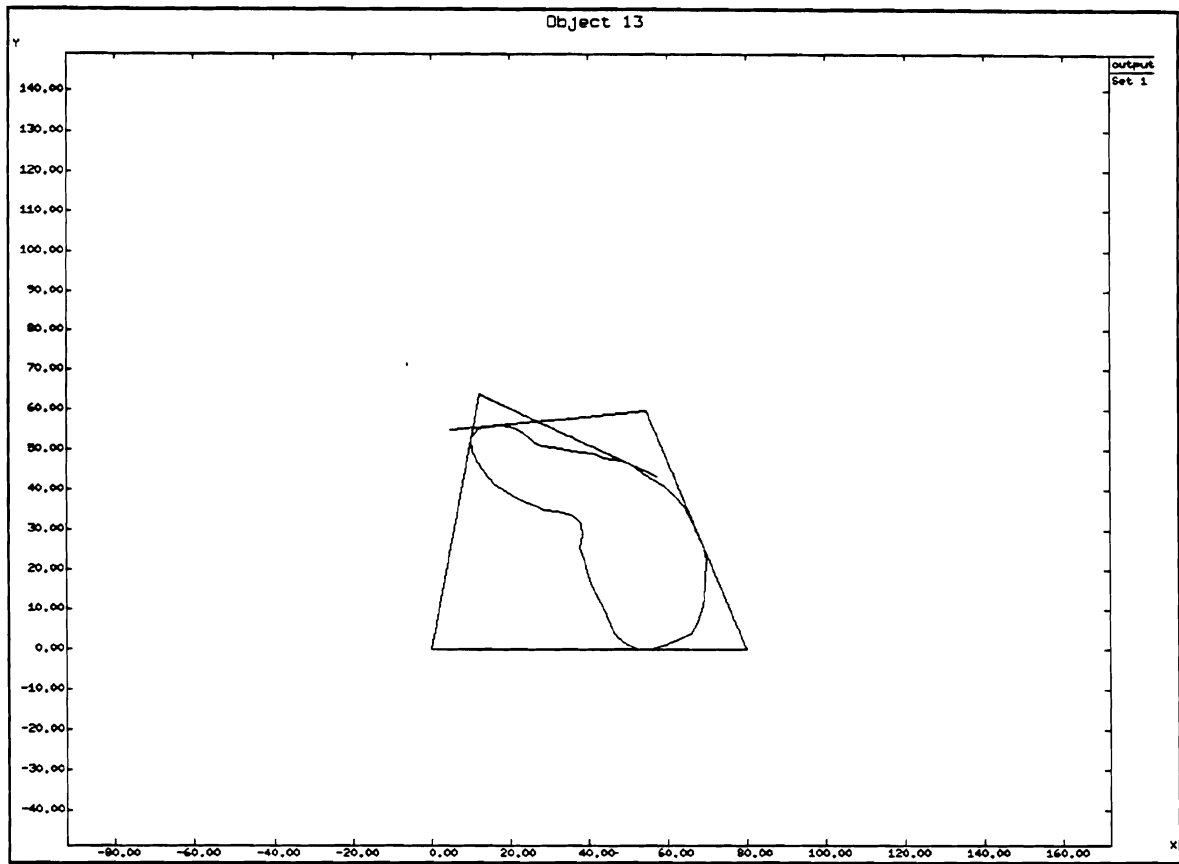
$A = \begin{matrix} 0.0000 & -0.6419 & 0.6435 \\ 1.0000 & -0.7668 & -0.7655 \\ 40.0000 & 30.4049 & -31.2312 \end{matrix}$

$\det(A) = 38.9082$

$f_0 = 1.6111 \text{ N}$ $-1 \quad 1.2136 \quad -0.0124 \quad 0.0253$ -0.1937
 $f_{12} = 3.2624 \text{ N}$ $A = \begin{matrix} 0.0158 & -0.6616 & 0.0165 \\ 1.5697 & -0.6599 & 0.0165 \end{matrix}$ $b = \begin{matrix} -3.1511 \\ 71.4011 \end{matrix}$
 $f_{22} = 2.9534 \text{ N}$

This grasp is stable.

Figure 18: Grasping an Elliptical Object



Based on breakaway at 0.1 N-m: $f_{11} = 1.8558 \text{ N}$
 $f_{21} = 3.5514 \text{ N}$

$d_0 = 55.9 \text{ mm}$ $\theta_{a11} = 101.0 \text{ deg}$
 $d_{11} = 53.9 \text{ mm}$ $\theta_{a12} = 103.4 \text{ deg}$
 $d_{12} = 39.7 \text{ mm}$ $\theta_{a21} = 112.9 \text{ deg}$
 $d_{21} = 28.2 \text{ mm}$ $\theta_{a22} = 72.8 \text{ deg}$
 $d_{22} = 39.8 \text{ mm}$

$A = \begin{bmatrix} 0.0000 & -0.4124 & 0.0994 \\ 1.0000 & -0.9110 & -0.9950 \\ 55.8951 & 24.6475 & -20.5449 \end{bmatrix}$

$\det(A) = 21.9743$

$f_0 = -0.3381 \text{ N}$ -1 1.9679 -0.2740 0.0228 -1.4497
 $f_{12} = 3.1571 \text{ N}$ $A =$ -1.5961 -0.2528 0.0045 $b = -1.7349$
 $f_{22} = -1.4868 \text{ N}$ 3.4390 -1.0489 0.0188 89.4625

This grasp is NOT stable.

Figure 19: Grasping an Irregular Object

the fingertip will contact an object before the inside surface of the finger. Second, as described above, if any of the three forces are negative. Third, if there is no solution to the matrix equation. Again, this analysis is based on the very conservative assumptions outlined earlier. The computer simulation results show several cases which in fact would “settle” into stable configurations, as well as cases which were unacceptable because of fingertip contacts³.

One result of the simulation has been the justification of the finger design. By running the program on a wide variety of object shapes, it has been shown that the finger will achieve form closure for at least one range of approach angles for almost every shape. With additional stability provided by friction contacts in most real situations, and the resistance to moments provided by line contacts, the finger will achieve form closure in many more situations. But the real significance of the result is that form closure can be achieved without precomputing the grasp and without force feedback. By simply sensing the contact positions and the joint angles, not only can we determine a sufficient condition for grasp stability, but we can do so without any complicated planning algorithm. The process will be complicated by an extension to three-dimensional grasping, but these results are significant for grasps involving objects with constant cross-section—a large percentage of the objects encountered in the real world.

A Simple Grasp Planning Algorithm

In order to consider how the hand described previously will interact with its environment, a basic outline of a typical grasping sequence was developed. This relies on the stability results developed earlier and uses a modification of the computer simulation illustrated previously to test its viability.

The basic objective of this algorithm is to to implement a *grasping by groping*

³In practice, these are viable configurations, however, they require the a consideration of specific fingertip shapes and contact interactions.

philosophy and thus keep the planning simple. As mentioned in Chapter One, various researchers have shown that it is necessary to use active sensors to supplement information provided by such remote sensors as vision or laser rangefinding[21, 22, 33] and that human psychological research has defined a number of *exploratory procedures* which require the stable apprehension and movement of objects to determine such structural properties as weight and volume[16]. In situations where there is little *a priori* knowledge of object characteristics, it is not possible to implement sophisticated grasp planning routines—these require detailed object information to calculate the position of fingertip contacts.

Because this finger design will passively shape itself to an object, we can often obtain a stable grasp with no more than the approximate spatial location. In addition, the iterative nature of this algorithm will allow us to learn about the shape of the object by combining contact information from successive grasps. There are six primitives involved in this process:

reach The arm is moved until the palm contacts the object.

retract The arm is moved away from the object. These are gross manipulation tasks as opposed to fine manipulation and thus may be relegated to the robot arm controller. However, tactile sensors on the palm must be used to sense contact in **reach**.

flex The fingers are closed until contact is made with both joints. (Contact with only the second joint can indicate several things, among them, the object is too far away or the object is too small for an enveloping grasp). Interaction with the robot arm is necessary at this stage to attempt to keep the joint angles as close as possible to each other, which will center the object in the grasp.

unflex The fingers are opened.

squeeze(τ_1, τ_2) The torques on the two motors are increased to τ_1 and τ_2 .

closure This is a boolean function which incorporates the computation required to determine whether or not a stable grasp can be obtained. In the event form closure is possible, it would also compute τ_1 and τ_2 .

A simple planning scheme could be as shown in Figure 20. The “simple strategy” mentioned above could involve computation of a more appropriate approach angle based on learned knowledge of the object shape. In Figures 21 and 22, we show an implementation based on a 5 degree change in approach angle. The graph shows the final stable configuration. Although this is blind groping and does not incorporate any knowledge of desirable conditions, in these two examples, as well as most of many others tried, stability was eventually achieved. In fact, the only regular shape which was not successfully grasped was a circle; without friction, the fingers are unable to resist moments about the center of the circle and stability (as it is defined here) is impossible.

Other Analysis

One area for further research involves experimentation with the hand to test the utility of these theories. It is also necessary to extend our grasping model to three dimensions and to include friction effects. With a knowledge of the coefficient of static friction at finger contacts, the frictional reaction forces can be calculated and stability predicted for cases that are rejected by our approach. However, in the situation where these frictional forces cannot be calculated and the coefficient varies or is unknown, it is necessary that stability can be maintained with frictionless contact.

The analysis of the stability of a grasp in three dimensions relies on the use of wrenches with six components. This complicates the computation, but the equilibrium conditions give six equations to calculate the contact forces necessary for stability. But it appears that a general analysis is not necessary or useful for this specific end effector. Instead, five analyses, one for each grasping mode, will be performed. This will allow for more efficient computation of the stability conditions.

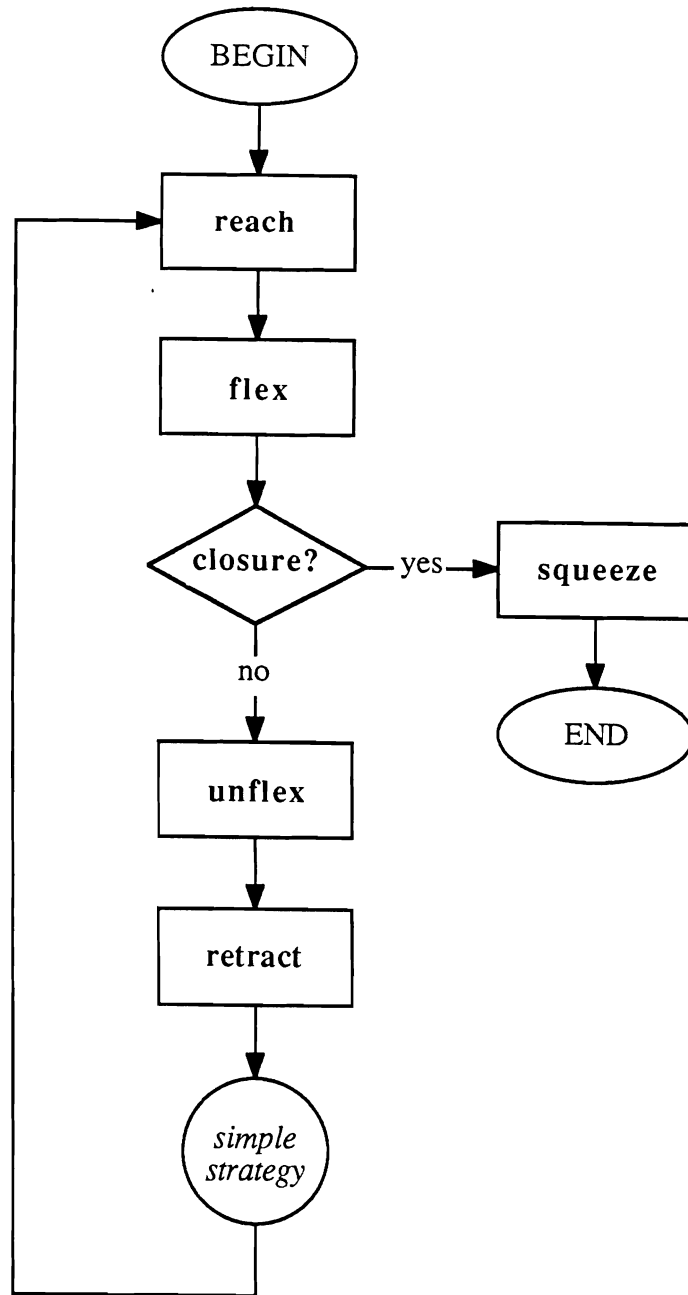


Figure 20: An Algorithm for Grasping Unknown Objects

The choice of which grasp type to use for a specific sensed object will rely heavily on these derivations. The use of three fingers and a palm in spatial manipulation can provide the seven contacts required for form closure without friction[10], but only with correct hand and arm positioning. The method used to choose grasp mode and approach strategy is a subject of future research.

Chapter 6

Conclusion

This thesis has presented the design fundamentals for a class of robotic end effectors. In doing so, the intent has been not only to communicate the details of the design, but to illuminate the process as well. Given the problem presented in Chapter One, and subject to the philosophy described in Chapter Two, the design described in the remainder of the thesis was synthesized. However, the progression was not that orderly. Although each individual approaches the uniquely creative process of design differently, for this author it is never the simple orderly progression outlined here or in various texts on the subject. Rather, it is more a random brainstorming which moves from idea to idea until eventually a possible approach is found and tested, usually to be rejected. Left out of the thesis, but nonetheless important, are the many blind alleys and frustrating twists and turns followed by the designer.

Because the hand has only four actuators, there are only four variables over which it is possible to exert control. However, the hand has seven degrees-of-freedom: two per finger, and one for the finger/palm relationship. These “extra” degrees of freedom are dependent upon the object shape, as described in Chapter Four. Although locating the grasping operation as much as possible in the mechanism has simplified most apprehension tasks, it also limits the versatility for other tasks which require more degrees of freedom or a different set of primitives.

However, this design is a compromise between many extremes: it is less complicated, less expensive, and easier to control than existing robot hands, yet more complicated, more expensive, and harder to control than simple grippers. In Chapter Two the idea of mechanical intelligence was introduced. Rather than expect to duplicate the human brain, which can perform miracles with less than perfect tools, it is more realistic to approach a design problem from both points of view; that is, to create more intelligent mechanical devices, which, combined with better control techniques, will significantly increase performance.

It is also important to consider the strengths and weaknesses of control techniques and planning methods in the design of any robotic or automatic machinery, just as the strengths and weaknesses of a gear or motor are considered. This approach has been used here, and the resulting mechanism implements in the mechanical design many primitives that would otherwise be left to the control. The simplicity of the planning algorithm presented in Chapter Five is significant in itself, but there is a broader result: complex tasks such as grasping are most efficiently performed with a combination of mechanical and artificial intelligence. The mechanical techniques have been presented here; the control techniques and planning methods necessary for other tasks are subjects for future work.

Future Research Topics

The body of research which is concerned with grasp planning and control has almost universally considered a complex hand model. The uniqueness of the hand design presented here requires that a new framework be built which is based on its operation and which includes enveloping grasps as well as limited fingertip grasping.

This means that the analysis of Chapter Five must be extended. Rather than consider only a planar situation, a three-dimensional analysis must be performed. And the five grasps possible with the hand must each be considered in detail. The

results will allow accurate planning algorithms to be implemented for the different types of situations likely to be encountered by the hand. In addition, the analysis must be extended to dynamic situations and to perturbations away from stability. A rigorous consideration of these conditions is essential to intelligent control of the hand.

Appendix A

The UPenn Hand

The main body of this thesis has been concerned with presenting a general class of end effectors for various applications. However, the main purpose behind the synthesis of these concepts has been to produce a tool for use in the research environment. This device has been dubbed the UPenn Hand. In this section will be presented some specific details of this mechanism.

The laboratory environment, especially the robotics research environment, places special demands upon an end effector. In the General Robotics And Sensory Perception (GRASP) Laboratory at the University of Pennsylvania, the following requirements are anticipated:

Because a number of individuals, each with different research projects, use the robot arms in the lab, mechanisms must be easily mounted and dismounted from each arm. At present, a single Puma arm may have attached to it a simple gripper, a UPenn Hand, a force/displacement sensor, a laser rangefinding device, a compliant wrist sensor, and a set of stereo cameras, all in one day. Quick and easy mounting and dismounting is essential to reduce the robot downtime. In addition, site visits and special demonstrations may require several experiments to be shown within a very short period of time. The UPenn Hand is completely self-contained, and connected to the arm by means of a quick-disconnect device. One half of this is permanently

connected to the lab arms, and all mounted devices connect with it in the same manner. Power and sensing cables are terminated at the hand with connectors. The hand can be completely mounted and dismounted in seconds.

The hand itself is under the same constraints as the arms. Individual researchers often require completely different configurations. To accommodate this, the fingertips, first joint inside surfaces, and palm of the hand are easily removed, to be replaced by tactile, force/moment, or other specialized sensors. Appendix C discusses these instruments in more detail. Although several hands are being made, there will still be a need for reconfiguration within each one, so simple screw connections are provided at the palm and fingers.

The same hand can consecutively be asked to pick up a hammer, then a fragile glass. The breakaway mechanism discussed in the next section allows variation in compliance, available in real-time and from the control program, to accommodate this requirement.

Because research funds are used to pay for the hands, economy is important. For this reason, the UPenn Hand has three fingers which are essentially identical. This lowers the fabrication costs significantly, and also reduces the inventory of spare parts necessary. Experimental setups are notoriously unreliable, so this modular design allows repairs to be made quickly and inexpensively. Although the palm components are unique in each hand, the drive motor, encoder, potentiometers, and some of the transmission components are the same for all of the three fingers and the palm movement. The majority of the fabrication is performed on NC milling machines through an outside independent machine shop. This further reduces the cost and allows for additional hands to be made easily.

The physical size of the UPenn Hand is approximately that of a human hand. This is to accommodate a range of sensing and manipulation experiments that are part of the GRASPlab's collaboration with human psychologists, as well as to match ongoing research. The robot arms used in the lab are Puma 560's, which have a

maximum payload of about 2 kg. It is also important to limit the distance an end effector extends from the mounting plate, as a limiting factor of arm performance is the moment about the wrist.

Although these requirements are more demanding than those required of the same device in, for example, an industrial environment, where it may be expected to perform several sets of tasks over and over with little reconfiguration, there are advantages to this application. Because the lab environment is rigidly controlled, there is no need to protect the hand from temperature extremes, dirt, moisture, other heavy equipment, or from excessive electro-magnetic interference (EMI). And because the number of cycles required of the hand is relatively low, long life is not a crucial requirement; redesign and replacement is more likely than wear.

The wiring and sensors do not need to be ruggedized either. The UPenn Hand has much of the cabling for the sensors outside of the mechanism envelope, which allows for easier removal, as well as simpler internal design. It is felt that sensor design will change dramatically over the useful life of the hand, and it is not prudent to lock the device into one specific arrangement.

The hand is expected to be used extensively in a cooperative arrangement with vision and other remote sensing devices. Most experimentation in the lab uses white objects to allow for more accuracy and to differentiate shadows from surfaces with different values. Although recent research is focussing on objects of varying colors, the hand has been made with a black dye anodization in order to reduce reflection and to separate it from the environment.

Figure 23 shows a conceptual sketch of the UPenn Hand. Figure 24 shows a scale assembly drawing of the first version. Below are listed some specific details, based on the first prototype.

- Mass: 1.5 kg (3.3 lbs)
- Distance between palm and arm mounting plate: 8.0 cm (3.2 in).

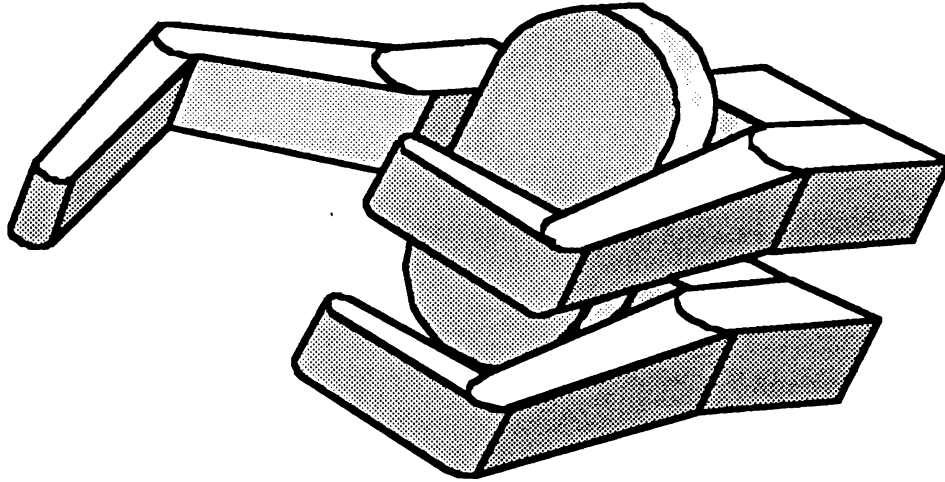
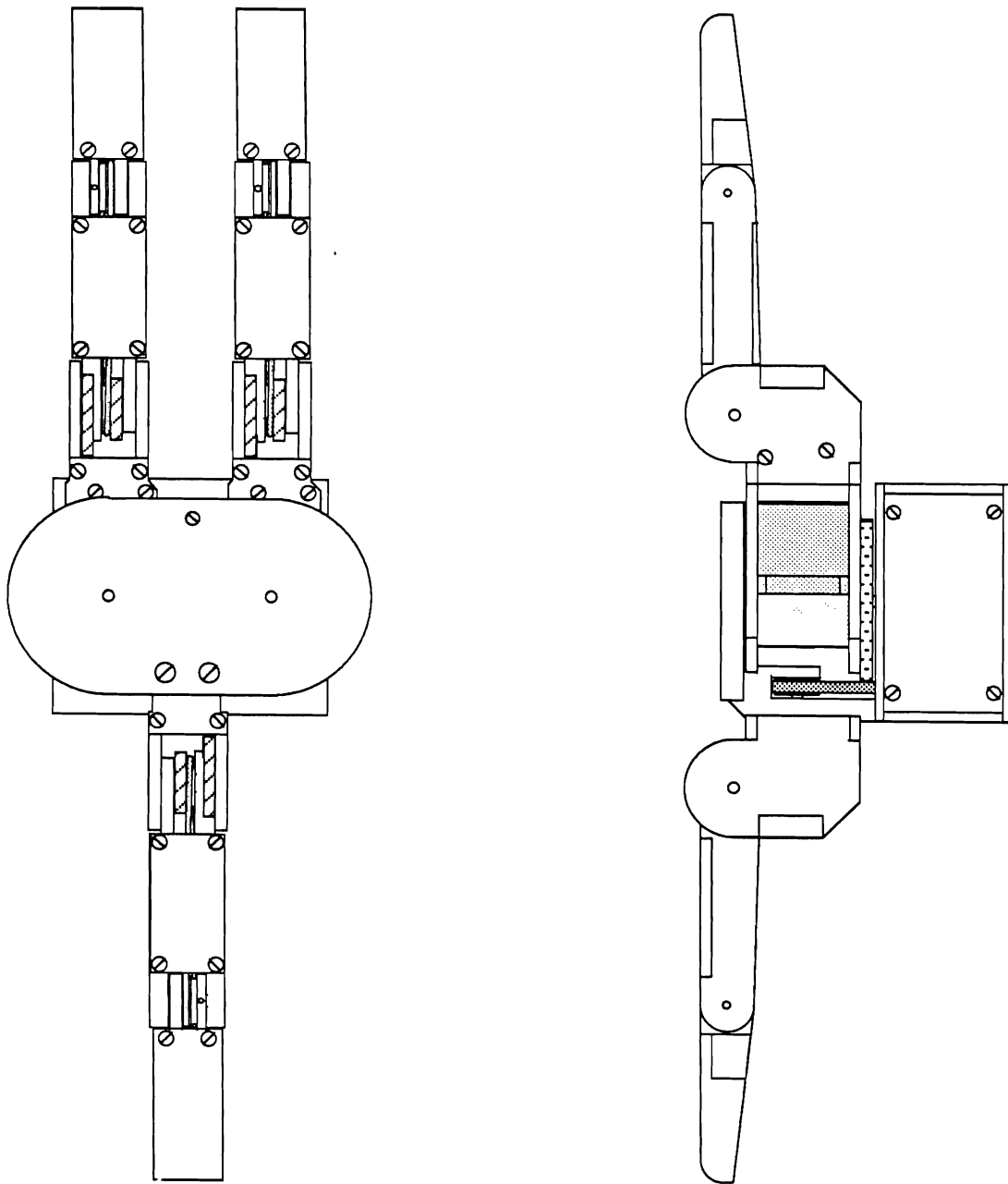


Figure 23: The UPenn Hand

- Finger length: 11.5 cm (4.5 in).
- Finger Width: 2.25 cm (0.875 in) at base, 2.0 cm (0.775 in) at tip.
- Palm Size: 6.0 cm (2.2 in) by 10.0 cm (4.0 in).
- Joint Ranges: 135 degrees for joint one, 90 degrees for joint two.
- Maximum Fingertip Force: 50 N (11.0 lbs) dynamically, 225 N (49.5 lbs) statically.
- Fully Open to Fully Closed, Minimum Time: 0.20 seconds.

The design of the UPenn Hand is contained in a set of 104 mechanical drawings drawn on a Macintosh II with the CAD program MacDraft. This collection is titled the End Effector Design Drawings (EEDD). An example drawing of part of a finger base is found in Figure 25. Several of the novel aspects of the design are protected by pending patents.



The UPenn Hand
Version I

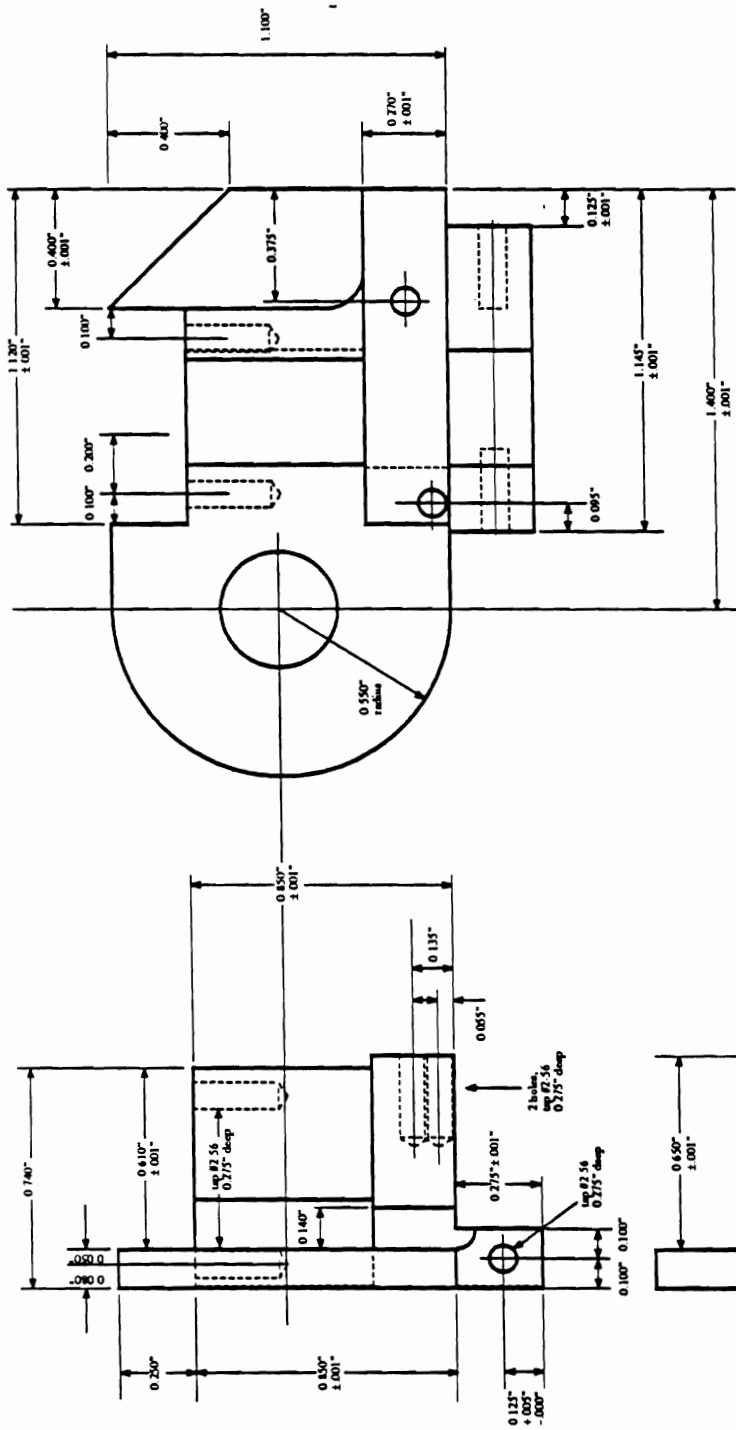


Figure 25: A sample drawing from the EEDD

University of Pennsylvania CIS Department - GraspLab End Effector Design Drawings	E4.02	Finger Base, 48 tooth side piece	Material: Aluminum
	1/16/89		Finish: Black Dye Anodized
			Quantity:
			Size: B#
			Drawn by: Nathan Ulrich
			Checked:

Appendix B

A Rotary Breakaway Mechanism

The functional behavior of the actuation mechanism for a two-jointed compliantly coupled finger has been presented in Chapter Four. This rotary breakaway mechanism, invented specifically for application in these fingers, is an interesting device on its own. It combines the functions of a variable torque clutch, differential, and brake into one compact device integral with the actuation and gear reduction of the fingers. This appendix will present the specifics of this design.

The operation can be most easily explained in reference to Figure 26, which is adapted from the fabrication drawings for the UPenn Hand. At the core of this mechanism is a non-backdrivable gear reduction of some sort. In this case, a worm gear is used. Spur gear pinion 10 is the input of the device, which can be driven via another gear which is connected to an actuator. When pinion 10 is turned clockwise, it screws into worm 30 and compresses rubber spring 50. If there is sufficient torque applied at 10 to overcome any torque applied at worm wheel 32, then after spring 50 is compressed to a certain point, worm 30 will turn with pinion 10 and worm wheel 32 will also rotate. Worm 30 is held in place by the preloaded bearings shown, and pinion shaft 12 is supported by the screw threads in worm 30 and by slide shaft 40. Slide shaft 40 is free to rotate around its bearing.

If there is sufficient resistance at worm wheel 32, then pinion shaft 12 can be

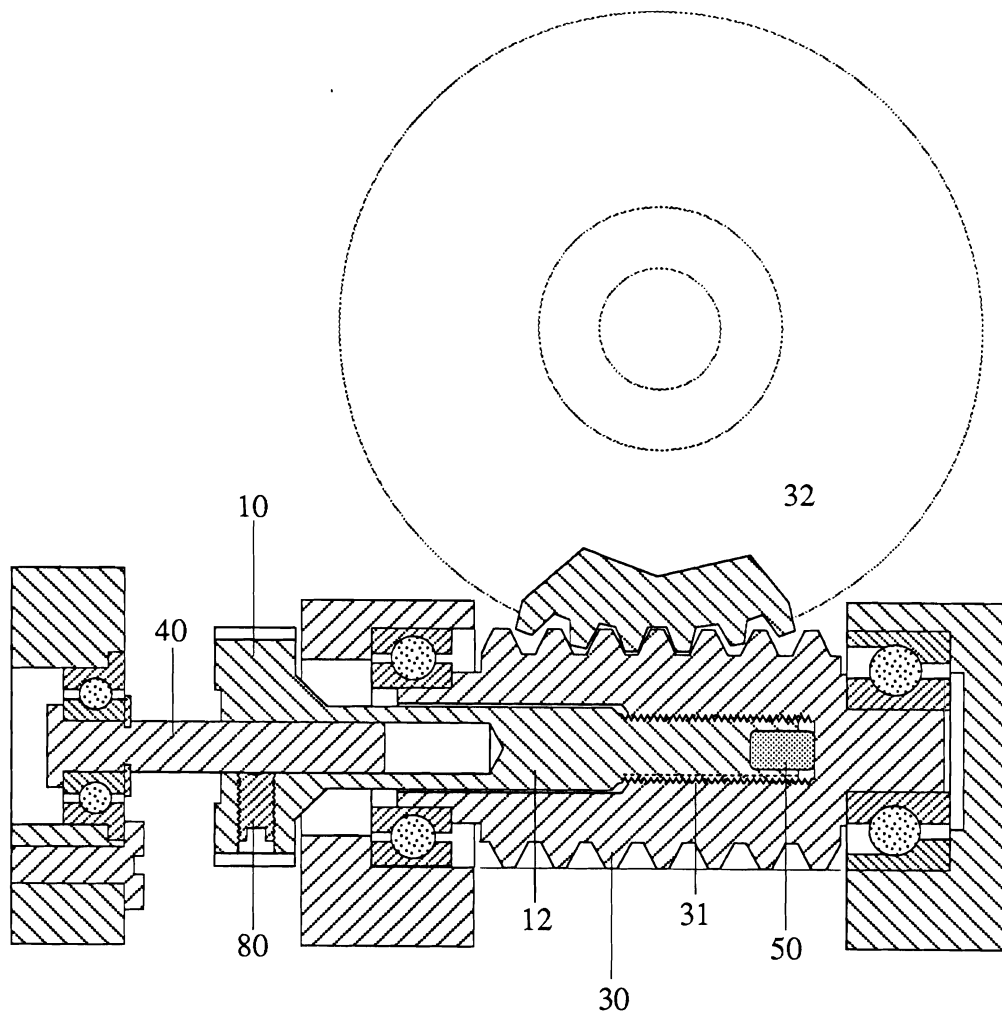


Figure 26: A Rotary Breakaway Mechanism

screwed clockwise into worm 30 and compress rubber spring 50 to various levels. The frictional resistance in threads 31 will vary depending on the axial force caused by spring 50. If pinion 10 is turned counter-clockwise, then worm 30 will also turn counter-clockwise, as long as there is no resistance at wheel 32. When a resistive torque applied at wheel 32 is sufficient to overcome the frictional force in the threads, then pinion shaft 12 will unscrew from worm 30, causing worm 30 to stop rotating and therefore causing wheel 32 to stop rotating. Pinion 10 will continue to unscrew from worm 30 until it reaches the limit of its range of motion.

Optionally, soft set screw 80 can be added to the mechanism. When this is tightened on slide shaft 40, then a resistance to the movement of pinion shaft 12 on slide shaft 40, and therefore a resistance to the unscrewing of pinion shaft 12 from worm 30, is added. This means that a constant torque—of a value dependent upon the force in set screw 80—must be maintained on wheel 32 to allow pinion shaft 12 to continue to unscrew from worm 30.

Rubber spring 50 could be replaced by other components, including a split collet, a helical coil spring, or a Belleville washer.

In operation in a finger transmission, the worm wheel output is connected to the first joint of the finger, while the finger actuator drives the second joint through another worm gear reduction with no breakaway mechanism or clutch. A movement of the finger actuator always results in motion of the second joint, but only moves the first joint when the breakaway mechanism has not broken away. A closing of the finger corresponds to a counter-clockwise motion of pinion shaft 12, which would tend to unscrew it from the worm 30. However, if the rubber spring is compressed, then the frictional force in the threads will resist the unscrewing and motion of the pinion will result in motion of the worm and motion of the first joint of the finger. When a resistive torque around the worm wheel, caused by object contact on the first joint, is sufficient to overcome the frictional force in the threads, then the pinion shaft starts to unscrew from the worm, and the mechanism “breaks away.” This causes the first

joint to stop, but because the worm gear is non-backdrivable, it maintains the contact force on the object. If the object happens to shift, then the friction caused by set screw 40 will cause the first joint to start moving until it contacts the object again.

Because the second joint is rigidly attached to the motor actuator, if the first joint has contacted an object and broken away, then the second joint will continue to rotate until it contacts the object as well. This causes a compliant behavior of the finger similar to that of the last two joints of the human finger.

If the first joint breaks away, then the finger can be reset by completely opening it against its stops, which will cause the pinion shaft to screw back into the worm. How much motor torque is applied at this point determines the first joint torque which will cause breakaway to occur. This allows the breakaway torque to be adjusted simply by a motion of the finger, which will allow the same fingers to grasp eggs and hammers.

There is a great deal of variation in performance that can be accomplished by the choice of materials in the screw threads, in the worm, in the soft set screw, and in the spring. Wear in the screw threads and in the spring also can cause variations of the material properties, but these have little effect on the performance of the mechanism. The only requirement is that the spring have predictable enough hysteresis that the breakaway torque can be accurately predicted from the resetting torque applied. Experience with prototypes has shown that the breakaway torque can be accurately predicted—to an accuracy of .5 percent—by simply experimentally determining a scalar multiple of the motor current applied at resetting of the finger. The range of breakaway values which can be achieved depends on the materials selected for the screw threads and the material used as the spring.

The latest finger prototype, which uses this breakaway mechanism, has shown the usefulness of this method of compliance. Because the fingers are not backdrivable, fingers will conform to object shape and hold on like a vise. Multiple object contacts are achieved for almost every shape tested, and the computer simulation shown in Chapter Five further validates the use of this mechanism in finger actuation.

In the UPenn Hand, the fingers are actuated by means of 48 pitch worm gear reductions. The motor drives a 96 pitch 24 tooth pinion which mates with two 32 tooth gears. One of these is attached through the breakaway mechanism to a worm and a 48 tooth worm wheel. The other is directly attached to 30 tooth worm wheel. The threads on the pinion shaft are 4-40, and 1/16" diameter rubber section is used as a spring. The entire finger actuation, including the breakaway mechanism, gear reductions, and finger base pivot, measures approximately 2.25 cm (0.875 in) by 3.5 cm (1.4 in) by 5.0 cm (2.0 in). Within this space are also contained some wiring connectors, finger pivot bearings, and motor mountings as well.

The mechanism itself has yet to be accurately modeled. Currently, a predictive model based on experiment has sufficed. However, if the mechanism is to be used in other applications or if academic interest prompts it, a investigation of the tribological basis of its operation will be undertaken.

Appendix C

Control and Sensing Issues

One of the goals of a medium-complexity end effector is to reduce the control system to a manageable size. However, the architecture and performance of this system is still important. Some of the same principles governing the mechanical design play a role in the electronic design—simplicity, ease of use, robustness, and economy are emphasized. This appendix presents the preliminary system architecture for the control system to be used with the UPenn Hand and a robotic arm.

Previous control systems have considered the hand and the arm as distinct mechanisms, both in the mechanical design and in the computer control. One of the goals of this end effector is to effectively attach an object to the end of a robot arm. Because the limited degrees of freedom of the hand do not allow fine manipulation of objects within the grasp, more attention must be paid to the use of the arm as a manipulation tool. The six or seven degrees of freedom of most robot arms is sufficient for this task, but it becomes important to consider the cooperative control of the hand and arm.

Control Architecture

Figure 27 shows the control architecture for the UPenn Hand. In this case, we are using a Puma 560 manipulator with the hand, but the scheme is sufficiently flexible

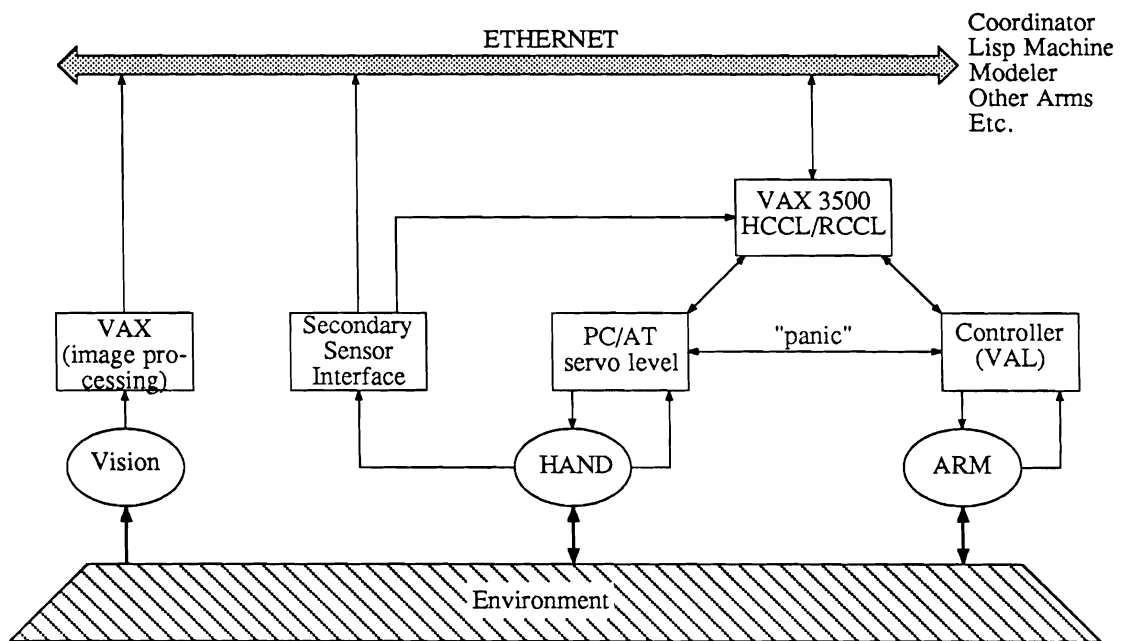


Figure 27: Control Architecture for the UPenn Hand

to accommodate other arms.

The servo control of the motors in the hand is done in a IBM PC/AT. Position and velocity are controlled based on feedback from an optical encoder mounted directly on the motor shaft. The encoders used are Disk Instruments miniature size 11 etched glass/LED encoders with 4000 counts per revolution and index. Force is controlled via feedback from tendon tension sensors which measures the torque around the second finger joints. These devices are composed of a 317 stainless steel beam and a pulley over which both halves of the tendon used to drive joint two pass. Semiconductor strain gages are mounted on the beam in a conventional bridge, giving an output directly proportional to the net torque applied around joint two.

Based on tests with a one-finger prototype under a similar control scheme, it is estimated that servo rates of greater than 800 Hz are possible. The AT communicates with a VAXstation 3500, a machine similar to the microVAX II, but with a different CPU and approximately 4 times the computational speed¹. This machine was chosen because its UNIX operating system (Ultrix 2.2) was compatible with that of the microVAX II (Ultrix 2.0); current robot control in the GRASPlab is run on microVAX II's and easy portability is essential. This machine will run a version of the Robot Control C Library (RCCL), a library of routines which are accessible from C programs developed in the UNIX environment. In addition, a new package of routines, called the Hand Control C Library (HCCL) has been written to allow parallel control of the hand. Because both RCCL and HCCL are implemented on the same machine, cooperative movement of the hand and arm is improved. However, since the actual servo control is accomplished on separate dedicated CPU's, this machine is free to do computationally-expensive planning.

The VAXstation is connected to the PC/AT and to the Puma controller (a PDP-11/73 which is supplied by Unimation with the arm) by means of parallel programmed

¹This machine was introduced early in 1988. Tests show a benchmark of approximately 1.58 million whetstones/second, and kinematic computational performance of approximately 2.2 times a VAX 11/785, 1.6 times a Sun 3/260, and 0.6 that of a Sun 4.

I/O. There is no need to synchronize machines, because all communication is buffered or DMA; however, because the Puma controller runs at a 7 ms interrupt rate, it is convenient to run the PC/AT and the VAXstation at a multiple of this: currently, the VAXen run at 28 ms, and the PC/AT at 1.75 ms. It is estimated that the interrupt rate on the VAXstation will be increased to 14 or 7 ms. The PC/AT and the Puma controller are also connected by a “panic” line, which allows for emergency communication between the two machines.

The sensors on the hand are divided into two groups: primary and secondary. Primary sensors are the optical encoders, the tendon tension sensors, and joint potentiometers. These are read directly by the PC/AT and used in the low-level control of the hand. Secondary sensors—tactile, fingertip force/moment, temperature, etc.—are not integral to the servoing of the hand and are therefore read by the VAXstation, to be used in the higher-level planning.

Vision, which is a passive sensing of the overall environment, is connected to this system via Ethernet, after being processed by its own machine. Other computers, such as a system coordinator, an AI processor, or a supercomputer such as the Thinking Machine, are connected through Ethernet in the GRASPlab.

The goal is to achieve a flexible working environment which allows communication between various sensors and devices in a way that aids coordination.

Sensors

Although the actual technical issues of the sensing system are beyond the scope of this document, the configuration of the sensors that are to be used is an important consideration; the UPenn Hand was designed partially as a “platform” for a number of types of sensors. This appendix will also present some aspects of the sensing system.

The following sensors are expected to be used with the UPenn Hand:

- *Tactile Array.* Three different tactile arrays have been designed. There are

three joint one arrays, which contain 72 taxels spaced 2.5 mm (0.100 in) apart, a palm sensor with 630 sites spaced 2.5 mm (0.100 in) apart, and a fingertip tactile sensor. The fingertip has two different taxel spacings. At the very tip, which is curved in a 6 mm (0.25 in) radius, there are 165 sites spaced 1.25 mm (0.050 in) apart. The remaining area has 54 taxels spaced 2.5 mm (0.100 in) apart.

- *Fingertip Force/Moment*: The fingertip tactile array sensor is attached to the finger body through a force/moment sensor. This is a semiconductor strain-gage based sensor which allows a determination of all six components of force and moment acting on the fingertip².
- *Texture*: It is possible to replace the fingertip sensor mentioned above, on any of the fingers, with a texture sensor. This is essentially a flexible element which acts much like a phonograph needle and determines the amplitude and frequency of vibrations excited by contact between the sensor and a surface. This can be combined with hand/arm dynamics to find precise textural information.
- *Temperature*: Also mounted at the fingertip is a specialized temperature sensor which tests the thermal conductivity of a surface or object by measuring the thermal resistance between two contacts.
- *Proximity*: There are two possible proximity sensors planned for the hand. One is a sonar-based instrument which measures distance by means of sound reflectance duration. This can be mounted at the palm. The other is a so-called “cat’s whisker,” which measures proximity by means of physical contact between flexible wands (cat’s whiskers) and the environment.

The above sensors are all processed by a machine dedicated to this task and

²The author would like to acknowledge the contributions of Michael Trull of Lord Corporation, who designed the sensors. Lord has generously agreed to provide the tactile, force/moment, and tendon tension sensors for the UPenn Hand.

the condensed information is used by the VAXstation in high-level planning and control. For example, the control scheme mentioned in Chapter 5 will rely on contact information from the tactile array sensors.

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