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Human Grasp Choice and Robotic Grasp Analysis

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ABSTRACT In studying grasping and manipulation we find two very different approaches to the subject: knowledge-based approaches based primarily on empirical studies of human grasping and manipulation, and analytical approaches based primarily on physical models of the manipulation process. This chapter begins with a review of studies of human grasping, in particular our development of a grasp taxonomy and an expert system for predicting human grasp choice. These studies show how object geometry and task requirements (as well as hand capabilities and tactile sensing) combine to dictate grasp choice. We then consider analytic models of grasping and manipulation with robotic hands. To keep the mathematics tractable, these models require numerous simplifications which restrict their generality. Despite their differences, the two approaches can be correlated. This provides insight into why people grasp and manipulate objects as they do, and suggests different approaches for robotic grasp and manipulation planning. The results also bear upon such issues such as object representation and hand design.

1.1 Introduction

In the broadest terms, there are two approaches to the study of grasping: the empirical and the analytical. The empirical approach studies grasping by humans and animals, the only successful grasping systems in our experience. The motivation is the often expressed and occasionally justified hope to learn from natural systems how to make good artificial ones. Unfortunately, we are rarely able to deduce how humans perform so well, and even when we can, human methods may not be right for mechanical systems.

In contrast, the analytic approach models grasping from first principles. Interactions between the hand and grasped object are modeled in terms of motions and forces, using the laws of physics. Here the problem is that the

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grasping process is so intrinsically complicated that many simplifications are required to make the analysis tractable. But this means that important effects are left out, resulting in models that only apply to carefully structured laboratory experiments.

Fortunately, these two approaches complement each other. Study of natural systems helps to assure that the analytic models are not overlooking important effects. Analytic work helps to explain why people do what they do – which provides insight for design and control of dextrous robot hands.

In the following sections we first review the results of studies of human grasp selection. We also review analytic grasp models and examine the assumptions upon which these models rest. Next we compare these approaches, and use them to evaluate each other. Finally, we consider directions for further investigation in the design and control of robot hands.

1.2 Human grasp choice

We begin by examining previous studies of human grasping. Next we describe our work in this area, including the construction of a grasp taxonomy and an expert system. The taxonomy is a method of organizing the range of human grasp types, and the parameters used in this organization reveal some of the factors influencing grasp choice. The expert system uses knowledge coded in the form of rules to deduce the appropriate grasp from object and task descriptions. It is in constructing the rule base that we learn the important properties of objects and tasks. Finally, we discuss the lessons to be learned from these studies of human grasping.

1.2.1 Previous studies of human grasping

The study of human grasping has long been an area of interest for hand surgery, for designing prosthetic devices and for quantifying the extent of disability in individuals with congenital defects or injuries. As a result, there is a substantial, empirical, medical literature on the grasping capabilities of the human hand. Much of the literature refers to six grasps defined by Schlesinger [1919] and summarized by Taylor and Schwarz [1955]: cylindrical, fingertip, hook, palmar, spherical and lateral.

Such a categorization leads to associating grasps with part shapes. Thus a sphere suggests a spherical grip while a cylinder suggests a wrap grip. However, when people use objects in everyday tasks, the choice of grasp is dictated less by the size and shape of objects than by the tasks they want to accomplish.

Even during the course of a single task with a single object, the hand adopts different grips to adjust to changing force/torque conditions. When unscrewing a jar lid, the hand begins with a powerful grip in which the palm is pressed against the lid for extra torque. As the lid becomes loose, torque becomes less important than dexterity and the hand switches to a light grip in which only the fingertips touch the jar lid. This task dependence was noticed by Napier [1956], who suggested that grasps should first be categorized according to function instead of appearance.

In Napier's scheme, grasps are divided into power grasps and precision grasps. Where considerations of stability and security predominate (as in holding a hammer or getting a jar lid unstuck) a power grasp is chosen. Power grasps are distinguished by large areas of contact between the grasped object and the surfaces of the fingers and palm and by little or no ability to impart motions with the fingers. Where considerations of sensitivity and dexterity predominate a precision grasp is chosen. In precision grasps, the object is held with the tips of the fingers and thumb.

More recently, Arbib, Iberall and Lyons [1985] have developed the concept of "virtual fingers," an abstraction whereby any number of real fingers that work as one are modeled as a single entity. For example, when picking up a pencil from a flat surface, two or three fingers are typically used in unison to oppose the thumb; the thumb would be described as one virtual finger and the set of fingers would be described as another.

Iberall [1987b] describes human grasping in terms of "oppositions," which are the basic hand configurations for applying forces to opposing faces of a grasped object. All human grasps are formed from a set of only three oppositions:

- pad, for forces between the pads of the fingers and thumb
- palm, for forces between fingers and the palm
- side, for forces between the thumb and the side of the index finger.

These oppositions are independent and may be used separately or simultaneously in a task. Each opposition is formed from two virtual fingers, one of which is always either the thumb or the palm. Thus picking up a pencil uses a pad opposition, turning a key in a lock uses a side opposition, and pounding with a hammer uses a palm opposition. Iberall also correlates this opposition/virtual finger approach to the previous categorizations of Schlesinger [1919], Napier [1956], and Cutkosky and Wright [1986b]. In Section 1.4.3, we relate these concepts to some of the analytical work on robotic grasping.

Finally, it is important to note that the human hand has evolved over millions of years as an organ used as much for sensation and communication as for manipulation. Thus in an approach similar to these studies of prehension, Klatzky and Lederman [this volume] have studied how humans use hands for exploration and perception.

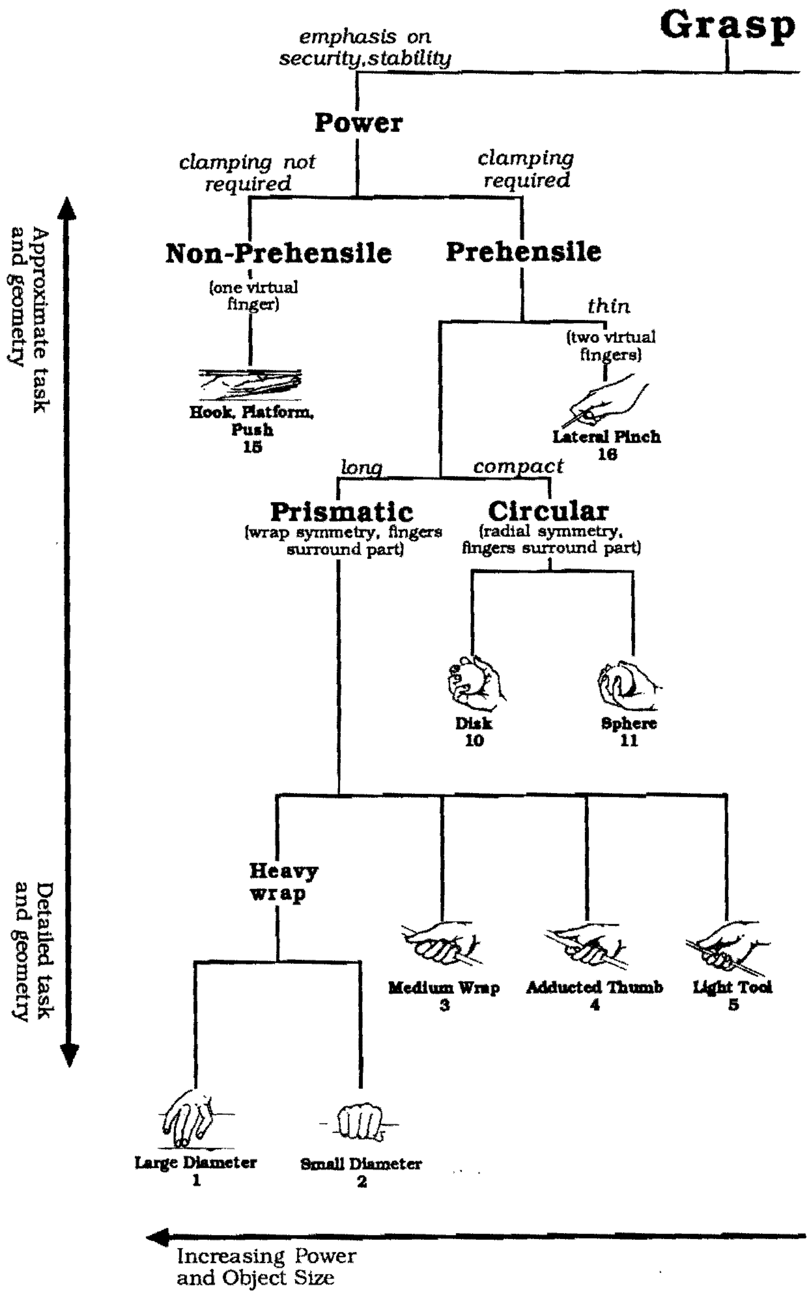

Figure 1.1: A partial taxonomy of manufacturing grasps, revised from [Cutkosky and Wright 1986b]. The drawings of hands were provided by M. J. Dowling.

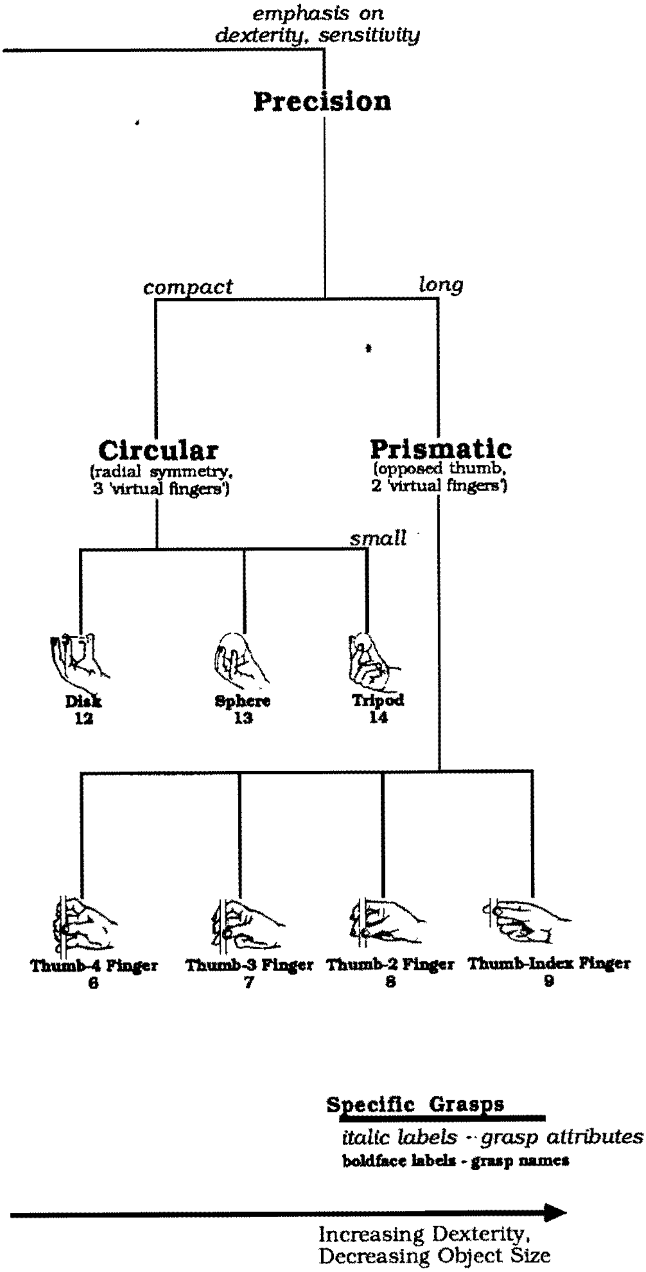

Figure 1.1 (continued): and are reprinted with the permission of the Robotics Institute, Carnegie-Mellon University.

1.2.2 A GRASP TAXONOMY

To study how humans choose grasps we have constructed a grasp taxonomy. The taxonomy is a systematic arrangement of the space of human grasps, and the organization of the taxonomy reveals some of the factors influencing grasp choice. Grasps can be placed on a continuum according to object size and power requirements. The taxonomy shows how task requirements (forces and motions) and object geometry combine to dictate grasp choice.

The taxonomy is based on observations of single-handed operations by machinists working with metal parts and hand tools. The machinists were observed and interviewed and their grasp choices were recorded as they worked. In addition, their perceptions of tactile sensitivity, grasp strength, and dexterity were recorded. Preliminary results of the study, and a resulting partial taxonomy of manufacturing grasps, were presented in [Cutkosky and Wright 1986b], and full details may be found in [Cutkosky 1989].

Starting with the two basic categories (power and precision grasps) suggested by Napier, we descend a hierarchical tree of grasps. As we move down the tree, details of the task and the object geometry become equally important so that in the final analysis, both task requirements and object shape play important roles in determining the grasp.

Once the basic choice between a power grasp and a precision grasp has been made, a combination of task-related and geometric considerations comes into play. Starting at the top of Figure 1.1, let us suppose that a power grasp has been chosen. The first question is: does the object need to be clamped to sustain forces from a variety of directions, or does it merely need to be supported? If it merely needs to be supported then a non-prehensile hook grasp (as used in carrying a suitcase) or a palmar support (as used by a waiter carrying a tray) may be adequate. If the object must be clamped, a prehensile grip is chosen in which the fingers and palm confine the object.

At this stage some basic geometric considerations become important: Is the object large? small? flat? thin? These subsidiary choices are illustrated in Figure 1.1. In the following, Grasp numbers refer to the numbers assigned in this figure. If, for example, a power grip is needed, and the object is small and flat (as in turning a key in a lock) then a Lateral Pinch (Grasp 16) will probably be used. If the object has a compact or approximately spherical shape then a Circular grasp (Grasps 10 and 11) is most likely. If the object is roughly cylindrical, then a wrap is chosen. Since many objects, including the handles of most tools, have cylindrical shapes, the power wrap represents a large family of grips.

While the different precision grasps appear to be motivated by part geometry, the decision to use one precision grasp instead of another may actually be task-related since many objects have several gripping surfaces with different shapes. For example, a light cylindrical object can be gripped either on the sides using the thumb and four fingers (e.g., Grasp 6) or it can be gripped by one end, using a circular finger placement (e.g., Grasp 12).

Trends in the taxonomy

Moving from left to right in Figure 1.1, the grasps become less powerful and the grasped objects become smaller. Thus the Heavy Wrap grips are the most powerful and least dextrous (all manipulation must be done with the wrist and even the wrist is restricted to a limited range of motions), while the Tripod (Grasp 14) and Thumb-Index Finger (Grasp 9) grips are the most precise. However, the trend is not strictly followed. A Spherical Power grasp may be either more or less dextrous than a Medium Wrap, depending on the size of the sphere.

Moving from top to bottom, or more precisely, from the trunk toward the leaf-nodes of the taxonomy, the trend is from general task considerations to details of geometry and sensing. Toward the top of the tree we are concerned with such basic considerations as whether the grasp must restrain the part, and with the overall shape of the object (long, compact, thin). At the lowest levels, we choose among similar grasps on the basis of geometric details (e.g., whether the object is closer to a disk or a sphere) and details of the task (e.g., whether sensitivity to vibrations is more important than the ability to apply rotations about the tool axis). However, the top-down trend is not strictly observed. For example, a small, flat object may provoke the choice of a Lateral Pinch near the top of the tree. In fact, the Lateral Pinch Grasp, though positioned above the Prismatic and Circular grasp types on the page in Figure 1.1, is essentially at the same level of detail.

The role of task forces and torques on grip choice is most apparent when the hand shifts between grips during a task. For example, in unscrewing a knob the hand shifts from Grasp 11 to Grasp 13 as the required torque decreases. Similarly, when holding a tool as in Grasp 3, the hand shifts to Grasp 5 as the task-related forces decrease and may adopt Grasp 6, a precision grasp, if the forces become still smaller. Task motions can similarly be used to distinguish among grasps with similar tools and force requirements. For example, when using a screwdriver to turn a screw, Grasp 4 is preferred over Grasp 2, because it orients the wrist better for applying rotations along the screwdriver axis.

The role of object size is most apparent when similar tasks are performed with different tools. For example, in light assembly work Grasps 12 and 13 approach Grasp 14, and finally Grasp 9, as the objects become very small. A related observation, brought out more clearly in developing the grasp expert system discussed in Section 1.2.3, is that sequences can be traced in the taxonomy, corresponding to adjustments that the machinists make in response to shifting constraints.

Limitations of the taxonomy

While the taxonomy in Figure 1.1 has proven to be a useful tool for classifying and comparing manufacturing grasps, it suffers from a number of limitations. To begin with, it is incomplete. For example, there are numerous everyday grasps, such as the grasp that people use in writing with a pencil, that are not included. It was also found that the machinists in our study adopted numerous variations on the grasps in Figure 1.1, partly in response to particular task or geometry constraints and partly due to personal preferences and differences in the size and strength of their hands. Such idiosyncratic grasps could usually be identified as "children" of the grasps in Figure 1.1.

1.2.3 An Expert System for Choosing Grasps

To clarify issues such as the roles of dexterity, sensitivity and stability in grasp choice, we constructed an expert system. This system, "Grasp-Exp," was designed to choose human grasps from initial information about the task requirements and object shape. Details of the system can be found in [Cutkosky 1989]. The system has gone through several iterations and has been tested informally with several machinists and researchers. In the tests, subjects were first given a tool and a task to perform and their grasp choice was recorded classified in terms of the taxonomy. Subjects were then asked questions about the tool and task by the expert system. Within the limited context of one-handed grasps in a manufacturing environment, we found that the system could usually predict how people would grasp parts or tools. Moreover, we found that where the expert system failed to identify the particular grasp that a person used, it picked a close relative that could also have been used to accomplish the task.

However, the purpose of the codification exercise was not to develop a program to predict what grasp a human would adopt under particular circumstances but to have a running, testable framework in which to try out hypotheses. In addition, the codification exercise forces one to be more careful about defining terms and organizing information. An expert system also makes it possible to ascertain what information about a task and object is required in order to deduce the appropriate grasp. Using this system also lead us to explore patterns or sequences among grasps, which provide insights for controlling robotic hands to manipulate parts.

Lessons from Grasp-Exp

Grasp-Exp shows that grasps can be uniquely and correctly determined by specification of object characteristics (e.g., size, shape) and *grasp attributes*, such as dexterity, precision, sensitivity, stability, and security. Rules in the system's knowledge base matched grasp attributes with the requirements of a task and characteristics of an object, as provided by the user. Several factors regarding geometric descriptions and grasp attributes became clear in the course of developing the system.

First, it is necessary to quantify grasp attributes so that different grasps may be ranked. We used scales of dexterity, precision, sensitivity, power, and stability, so that precision grasps tend to be at one end of the spectrum and power grasps at the other. Thus grasps in the center of the taxonomy show a mix of these properties. For example, the Light Tool grasp (Grasp 5) is classified on the taxonomy as a power grasp, as evidenced by its low dexterity and high stability and power. However, in discussions with machinists, and in our own experience with this grasp, we have found that it has good sensitivity to forces and vibrations – a characteristic of precision grasps.

Grasp attributes often occur in sets determined by the general type of task. Users found it difficult to assign quantities to terms like dexterity and sensitivity, so it was necessary to have the expert system ask additional questions about the force requirements, approximate object weight, and so forth. Often, it is easiest to ask such questions in terms of analogies: "Would you classify the task as most like a prying task? a tapping task? a pushing task? ..." This suggests that there are a relatively small number of prototypical tasks such as prying or tapping, each requiring a particular set of grasp attribute values.

We learned similar things about the description of objects. As with the grasp attributes, users found it difficult to quantify the size of an object (e.g., "Is the object large, medium, or small?"). A better reference is the size of the hand (e.g., "Is it bigger than a fist?"). We also found that the approximate geometric descriptions (e.g., compact, thin, prismatic) in the taxonomy were too vague. These descriptions have been extended to include the rough-object-shape and detailed-object-shape (long, thin, disk-shaped, rectangular, etc.). However, even this description is not sufficient, as the features of an object which are important for grasping may not be emphasized in this type of geometric information. In Section 1.5 we consider the question of appropriate representations for reasoning about grasping.

As with the taxonomy, Grasp-Exp permits us to examine the interaction between task requirements and object geometry in a sequence of tasks with a single object or in the same task with different objects. For example, consider precise manipulations of a light, compact object with a precision grip. Initially, Grasp-Exp may choose the precision disk grip. But as the size of the object grows smaller with respect to the hand, the selected grasp shifts to a tripod grip and finally to a thumb-index finger pinch.

Tactile sensing and grasp choice

Our work with Grasp-Exp shows that sensitivity to forces and vibrations must often be taken into account to correctly predict grasp choice. Iberall [1987b] also notes that humans balance the ability to sense with the

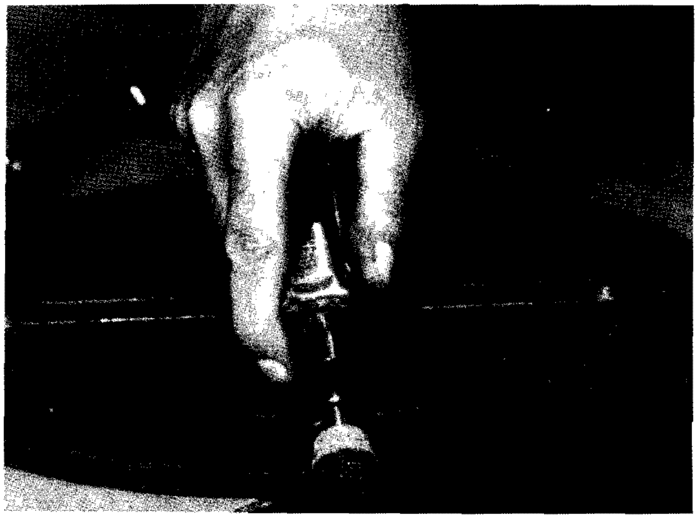

Figure 1.2: Although it is a power grasp, the Light Tool grasp (Grasp 5 in the taxonomy) shows good sensitivity (©IEEE, Cutkosky 1989).

ability to impart forces and motions during manipulation. Sensitivity is a characteristic of the precision grasps, which use small forces, limit contact areas to the ends of the fingers, and often separate finger positions widely.

In general, the hand becomes less sensitive to small forces and vibrations as more force is applied. One reason for this is the compliant structure of the fingers and palm [Howe and Cutkosky 1989]. When the hand is lightly loaded the skin effectively floats on soft subcutaneous pulp. The skin is thus decoupled from the more rigid bone and muscles of the inner structure of the hand. Small forces or motions from the object can cause substantial motion of the skin, where many sensors are located, resulting in good sensitivity. As the contact force increases, pressure beneath the skin increases and the skin and hand structure become coupled. The system becomes stiffer and task forces now produce smaller skin motion, so sensitivity decreases.

The placement of finger contacts also plays an important role in sensitivity. The mechanoreceptors responsible for our most acute tactile sensitivity are concentrated at the fingertips, so sensitivity improves if these areas are kept lightly in contact with the object. Also, separating the contacts from the center of compliance of the grasp means that when the object rotates, the motion at the contact location will be greater.

An example of these principles is the Light Tool Grasp (Grasp 5), shown in Figure 1.2. Unlike the other power wrap grasps, this one has good sensitivity, although the only topological difference is that the index finger is extended along the grasped object. This finger is not in opposition with the palm and experiences much smaller forces than the other fingers. The tip of the finger is kept in light contact with the object, and it is much closer to the origin of the task forces than the other fingers, which are located essentially at the center of compliance of the grasp. Thus small forces and vibrations produce comparatively large motions of the fingertip skin, resulting in good sensitivity.

1.3 Analytic approaches to grasp modeling and grasp choice

In this section we examine grasp analyses for robotics. These studies attempt to model the interaction between object and hand from first principles. For example, contact forces, kinematics, or compliance of the hand-object system are often included in a model. However, in order to make analyses tractable, many important factors are not included, and we consider some of these omissions and their implications.

Many analyses develop quality measures, which are used to evaluate the success of a grasp. We summarize the most useful measures in Table 1.1. Grasp choice is often then characterized as an optimization within constraints, with each author picking a different set of quality measures to optimize while treating others as constraints. These quantitative analyses, which have constituted the bulk of the work in grasping theory, do not treat large motions during manipulation, or prescribe a basis for selecting a particular type of grasp. Geometric and knowledge-based approaches have been suggested for this area.

1.3.1 Grasp modeling

As Figure 1.3 indicates, manipulation is complex, typically involving combinations of open and closed kinematic chains, non-holonomic constraints, redundant degrees of freedom and singularities. In addition, there are nonlinearities in the contact conditions between soft, viscoelastic fingers and grasped objects, and in the drive-train and actuator dynamics. To keep the analysis tractable, early analyses (e.g., [Hanafusa and Asada 1977b]) made the following assumptions, many of which are also found in current analyses of dextrous manipulation:

- rigid-body models with point contacts between the fingertips and the grasped object, often in 2-D
- linearized (instantaneous) kinematics
- quasistatic analysis (no inertial or viscous terms)

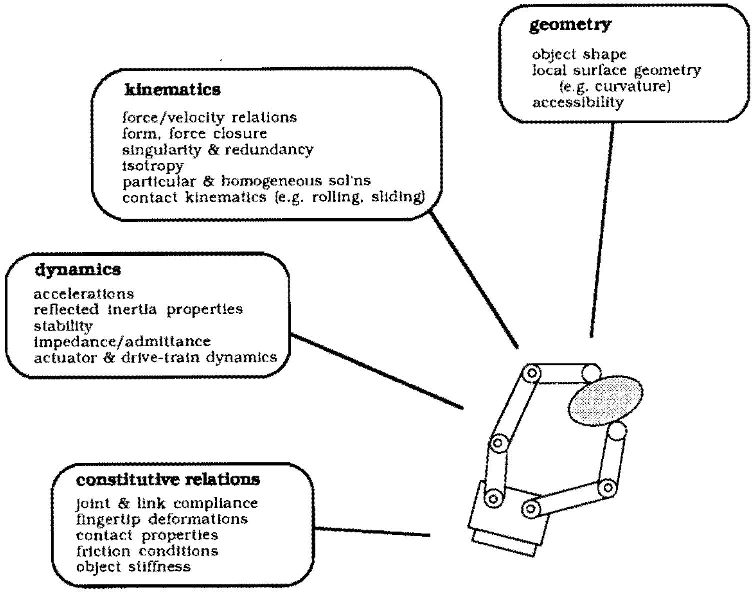

Figure 1.3: Issues in analytic modeling of grasping and manipulation (©IEEE, Cutkosky 1989).

- no sliding or rolling of the fingertips
- no cases with redundant degrees of freedom and no over-constrained grasps.
- assumed full knowledge of object and contact states, with no consideration for using sensory information during manipulation

Recent analyses, such as those by [Cutkosky and Wright 1986a; Nakamura, Nagai and Yoshikawa 1987; Ji 1987; Li and Sastry 1988], have relaxed some of these assumptions, although at the cost of greater complexity. Moreover, even the most sophisticated models involve the following simplifications:

- idealized models of the fingertips (e.g., point contact, or "soft finger" models with linear elastic deformation)
- idealized friction models (e.g., Coulomb friction) that ignore the effects of sliding velocity, material properties of the "skin," and the presence of dirt or moisture
- simplified actuator and drive-train dynamics, often ignoring elasticity, backlash and friction

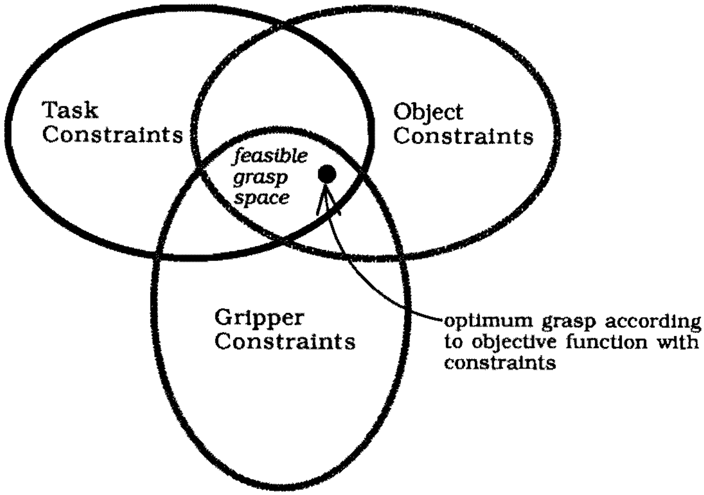

Figure 1.4: Analytic grasp choice: maximizing an objective function subject to task, object and gripper constraints (©IEEE, Cutkosky 1989).

- simplified representations of the grasped objects, treating them as smooth, rigid geometric primitives or polyhedra.

Based on the various analytic models of grasping and manipulation, a number of quality measures have been developed. Each measure provides a quantitative means of evaluating an important aspect of a grasp. For reference, these are summarized in Table 1.1. In Section 1.4 we evaluate the effects of the above simplifications and compare the quality measures with the empirically derived grasp attributes used in the expert system.

1.3.2 Analytic grasp choice as optimization

Many analyses treat grasp choice as constrained optimization. The problem of choosing a grasp based on analytic grasp models, quality measures, and constraints is illustrated in Figure 1.4. There are three overlapping sets of constraints arising from the task (e.g., forces and motions that must be imparted), from the grasped object (e.g., the shape, slipperiness and fragility of the object), and from the hand or gripper (e.g., the maximum grasp force and maximum opening of the fingers). Within these constraints is a space of "feasible grasps."

Choosing a grasp involves the definition of an objective function, which is optimized, subject to the constraints. The approach is conceptually straightforward, except that there is little agreement on which of the measures in Table 1.1 (along with additional geometric issues) should be in-

Compliance	What is the effective compliance (inverse of stiffness) of the grasped object with respect to the hand? The grasp compliance matrix is a function of grasp configuration, joint servoing, and structural compliances in the links, joints, and fingertips [Cutkosky and Kao 1989].
Connectivity	How many degrees of freedom are there between the grasped object and the hand? Formally, how many independent parameters are needed to completely specify the position and orientation of the object with respect to the palm [Mason and Salisbury 1985]?
Force closure	Assuming that external forces act to maintain contact between the fingers and the object, is the object unable to move without slipping when the fingers are locked? Formally, a grasp satisfies force closure if the union of the contact wrenches has rank 6 [Ohwovoriole and Roth 1981; Mason and Salisbury 1985].
Form closure	Can external forces and moments be applied from any direction without moving the object, when the fingers are locked? Formally, there is form closure, or complete kinematic restraint, if the intersection of all contact twists is a null set [Lakshminarayana 1987; Mason and Salisbury 1985]. For many tasks form closure is only required in certain directions.
Grasp isotropy	Does the grasp configuration permit the finger joints to accurately apply forces and moments to the object? For example, if one of the fingers is nearly in a singular configuration, it will be impossible to accurately control force and motion in a particular direction. Formally, the grasp isotropy is a function of the condition number of the grasp Jacobian matrix [Mason and Salisbury 1985; Kerr and Roth 1986]. Li and Sastry [1988] define similar grasp quality measures that are functions of the singular values of the grasp Jacobian.

Table 1.1 (Part 1): Definitions of analytic measures used to describe a grasp (©IEEE, Cutkosky 1989).

Internal forces	What kinds of internal grasp forces can the hand apply to the object? These forces are an important means of increasing friction at contacts. Formally, the internal grasp forces are the homogeneous solution to the equilibrium equations of the object. Thus, internal grasp forces can be varied without disturbing the equilibrium [Mason and Salisbury 1985; Kerr and Roth 1986].
Manipulability	While not consistently defined in the literature, a useful definition is: Can the fingers impart arbitrary motions to the object? Thus, a fully manipulable grasp must have a connectivity of 6, although some precision grasps have good manipulability in only a few directions, with the wrist and arm supplying further mobility. In addition, the rank space of velocities due to the joints must span the space of velocities transmitted through the contacts [Kerr and Roth 1986].
Resistance to slipping	How large can the forces and moments on the object be before the fingers will start to slip? The resistance to slipping depends on the configuration of the grasp, on the types of contacts and on the friction between the object and the fingertips [Kerr and Roth 1986; Cutkosky and Wright 1986a; Jameson and Leifer 1987; Ji 1987].
Stability	Will the grasp return to its initial configuration after being disturbed by an external force or moment? At low speeds, the grasp is stable if the overall stiffness matrix is positive definite [Nguyen 1988; Cutkosky and Kao 1989]. At higher speeds, dynamic stability must be considered [Nakamura, Nagai and Yoshikawa 1987].

Table 1.1 (Part 2): Definitions of analytic measures used to describe a grasp.

cluded in the objective function, and which should be used as constraints. Kerr and Roth [1986] establish a polyhedral region of "safe" grasps, bounded by friction limitations at the contacts. They define an optimal grasp as one that is furthest from the boundaries of the friction polyhedron, while also satisfying force closure and constraints on internal forces and actuator torques.

By contrast, Nakamura, Nagai and Yoshikawa [1987] search for a grasp that minimizes internal forces (and consequently, grasping effort) subject to constraints on force closure, friction and manipulability. If a safety factor is used in setting the friction constraints, this approach should give results similar to the approach that people seem to use, with forces a consistent percentage above the minimum required to prevent slipping [Ring and Welbourn 1968; Westling and Johansson 1984].

In a very different approach, Jameson and Leifer [1987] adopt a numerical hill-climbing technique in which a simplified three-fingered hand searches for positions that are most resistant to slipping, subject to constraints on joint torques and geometric accessibility. However, they cast the constraints as potential functions so that their effects are added to those of the objective function. In still other work, Li and Sastry [1988, this volume] define a "task ellipsoid," whose orientation and relative dimensions depend on the expected magnitudes of forces and moments during a task. Grasps are then compared according to the largest diameter of the task ellipsoid that they can encompass.

1.3.3 Other approaches to analytic grasp choice

The measures in Table 1.1 describe the kinematics and dynamics of a grasp, but there are clearly other factors involved in grasp choice. For example, if an object is to be picked up from a table, the grasp cannot place any fingers on the underside of the object. Other considerations include the size, shape and location of the center of mass of the object, the workspace of the hand, and the subsequent task requirements. Thus, a number of investigators have proposed geometric criteria for automated grasp selection [Lozano-Pérez *et al* 1987; Brost 1988; Tomovic, Bekey and Karplus 1987].

While there are numerous articles on grasp stability, force closure and quality measures for comparing different grasps, little has been proposed in the way of an overall strategy for grasp planning based on these measures. However, Ji [1987] outlines a sequence in which the first step is to find "grasp planes" defined by three fingertip contacts. He suggests several heuristics for locating possible grasp planes. The next step is to determine the arrangement of contacts about the periphery of the grasp plane. The grasps are checked for accessibility constraints (e.g., which parts of the object can the fingers actually reach?) and finally, task requirements are checked, possibly using a task-oriented quality measure such as that proposed by Li and Sastry [1988].

Several knowledge-based approaches, involving more detailed geometric descriptions than those in Grasp-Exp, are also being developed. Stansfield [1988] has built an expert system for robotic grasp choice using a two-stage model of grasping, with hand preshaping followed by object acquisition. This system generates candidate preshapes for grasps from symbolic, geometric object attributes, and considers the role of vision and tactile sensing in grasping.

Iberall *et al* [1988] are also developing an expert-system based approach to grasp choice. A high-level specification of a simple task is mapped into appropriate internal representations of the object, action, and hand. The system uses knowledge bases containing tool descriptions and rules for selecting oppositions and virtual fingers to generate a grasp.

1.4 Comparison of human and analytic grasp choice

By comparing studies of human grasping with analytical grasp models, we can evaluate the effectiveness of each approach. As a first instance, we consider the question "Given their numerous simplifications, how successful are the analytic models of grasps?" Since the simplifications used in most analyses represent approximations to real conditions, under particular circumstances any one of the analytic models may be a good approximation. The grasp taxonomy is useful here, making it easy to see which approximations apply to which sets of grasps. Study of the taxonomy reveals which grasps are likely to produce slipping or rolling of the fingertips, which have large areas of contact, or which have redundant degrees of freedom.

For example, the point-contact models are reasonably accurate for the precision Disk and Sphere grasps, where the contact areas are small compared to the diameter of the grasped object. On the other hand, a very-soft-finger model [Cutkosky and Wright 1986a] more accurately approximates the Tripod and Thumb-Index Finger precision grasps, where the finger pads conform to and even partially entrap the object.

Considering the range of grasps in the taxonomy, it is clear that the great majority of analyses have dealt only with fine-motion precision grasps. For the power grasps, most of the theoretical analyses are irrelevant since the fingers do not manipulate the part. Perhaps the best solution for power grasps is to assume complete kinematic coupling (with compliance) between the hand and the object, and to assign a set of friction and joint torque limits to the grasp.

Furthermore, with a few exceptions [e.g., Fearing 1986b], large motions of the object with respect to the hand have not been considered. It is also clear from the human studies that a combination of object, task, and hand properties must be considered. But few, if any, analyses have considered all three. Clearly, in order to determine which are the correct analyses and which are the fallacious approximations, we must test the predictions of these models in experiments with real robot hands.

1.4.1 HUMAN GRASPS IN TERMS OF ANALYTIC GRASP MEASURES

Although the analytic approaches to grasp choice involve many simplifications, the measures developed in the analytic work, and summarized in Table 1.1, can nonetheless be applied to human grasps. For example, all of the grasps (except the non-clamping hook or platform grasps) satisfy force closure, assuming extra contact wrenches due to friction. The non-clamping grasps are force closure, provided that external forces do not cause the fingers to detach from the object.

Many grasps do not satisfy form closure without friction. Particularly, if we know the direction from which the task forces are coming, then we do not need the added security of kinematic restraint. Figure 1.5 shows a person pulling on a wrench to tighten a large bolt. The principal task force is known and the hand adopts a "hook" grasp from the grasp taxonomy. There is no opposition between the fingers and the palm and therefore no ability to control internal forces. By contrast, if the same person were trying to free a sticky (perhaps rusted) bolt, a more conservative wrap grasp would be adopted to prevent the wrench from flying out of the hand if the bolt should suddenly come loose. When compared to the hook grasp, the wrap grasps have an opposition between the fingers and the palm, an ability to control internal forces, and an ability to apply both positive and negative forces with respect to the wrench handle. Only in extreme cases (e.g., washing dishes or handling a wet bar of soap) do we tend to use grasps that would satisfy form closure without friction.

In terms of the other analytic measures, human power grasps are less compliant, more stable and have a larger resistance to slipping than precision grasps. This is because power grasps are able to exert large internal forces, thus increasing the magnitude of frictional forces. Finally, power grasps have a connectivity of zero since the fingers do not manipulate the part. However, the precision grasps have high manipulability, and a connectivity between object and hand of at least 3 and often 6.

Many of the detailed grasp attributes in Grasp-Exp can also be correlated with the analytic measures. However, since the terms that people use for describing grasps are subjective, and depend on many subtle factors, the correspondence is rarely exact. For example, security decreases as the applied force increases. When people say they need a secure grasp, they implicitly take into account the magnitude of the forces in the task. Thus, manipulating a small object between the pulps in a two-finger precision pinch grasp may be perfectly secure (i.e. the object won't slip out of the grasp), but this is not considered a "secure" grasp.

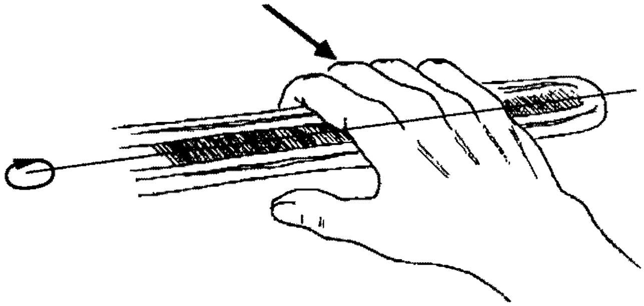

Figure 1.5: A Hook grasp is used to pull on a large wrench. The lack of closure is acceptable if the task force remains predictable.

As shown in Figure 1.6, grasp attributes used in the expert system correspond to analytic measures from Table 1.1 as follows:

- *Sensitivity* depends on many factors but is primarily related to how accurately the fingertips can pick up small small vibrations and small changes in force and position. Thus sensitivity is a function of grasp isotropy (if the fingers can impart forces with accuracy then they can also measure forces with accuracy) and stiffness (a compliant grasp is more sensitive to small changes in force).

- *Precision* is a measure of how accurately the fingers can impart small motions or forces to the object. Thus, precision requires light grasp forces, full manipulability and isotropy.

- *Dexterity* is similar to precision but implies that larger motions can be imparted to the object. Thus dexterity depends both on manipulability and the kinematic workspace of the hand (and often the wrist).

- *Stability* includes both the definition in Table 1.1, in which a stable grasp will return to its nominal position after being disturbed and the ability of the grasp to resist external forces without slipping.

- *Security* is related to stability, but is most closely associated with resistance to slipping.

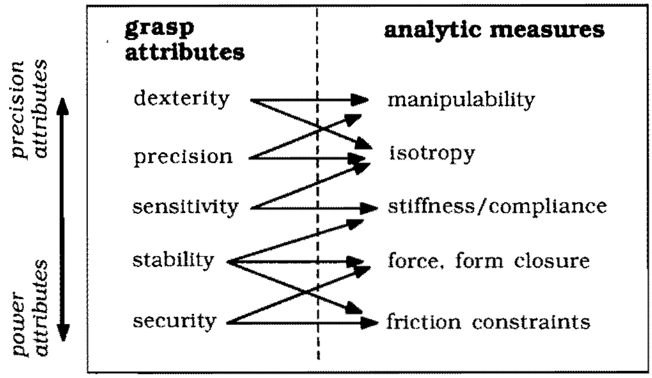

Figure 1.6: Human grasp attributes in terms of analytic grasp measures (©IEEE, Cutkosky 1989).

1.4.2 Grasp choice issues

The analytic measures are useful for comparing grasps, but the resulting constrained optimization approach to grasp choice is impractical for generating candidate postures. This approach requires specification of exact finger placements, and so requires search of a very large space of possible contact positions [e.g., Jameson and Leifer 1987].

Several workers have suggested that grasp choice is best approached as a two stage process: first a basic hand configuration or posture is selected, then the exact placement of the fingers is chosen [Ji 1987; Iberall *et al* 1988; Stansfield 1988]. Our experience with Grasp-Exp indicates that a knowledge-based approach using descriptions of the geometry and forces of the task and object can be used to generate candidate hand postures. From the taxonomy of Figure 1.1 we also see that there are a finite number of fundamentally different hand postures. If the search is done in this space it is a simple problem, and a relatively small rule-based system is capable of choosing a grasp based on object and task requirements. Stansfield [1988] and Cutkosky [1989] both suggest that about 100 rules are sufficient for this job. Ji's work [Ji 1987] outlines how heuristics might be combined with analytic concepts to generate grasps. In Section 1.5 we discuss questions of object representation for grasp planning, which can greatly simplify the generation process.

There is some question about which to consider first, the geometry of the hand and object, or the task forces. It seems that neither one should necessarily come first. Rather, these are simultaneous constraints and either one may prune off larger pieces of the search space initially. A good strategy is to first apply those constraints that reduce the search space fastest.

Once candidate grasps have been generated, the quality measures can be used for deciding between candidate grasps or optimizing the exact placement of the fingers. A rule-based system could also decide which of the analytical measures to use in assessing a grasp. This could be based on considerations about which of the simplifying assumptions (such as point versus soft-finger contacts) apply to a particular grasp. Note that the taxonomy is helpful in this, since choice of the correct approximations can be based on both the generic type of grasp and the particulars of the object and task. Alternatively, the system could decide which of the measures to treat as constraints and which to optimize, based on the circumstances.

Other work [Tomovic *et al* 1987; Iberall 1987b] suggests that once the basic posture is known, tactile sensing must be used to optimize placement of the fingers as the grasp is executed. Fearing [1987a] also shows that tactile sensing is crucial to robotic manipulation with large motion.

1.4.3 VIRTUAL FINGERS, OPPOSITIONS AND INTERNAL FORCES

An interesting sub-topic that surfaces in both the analytic grasp work and in observations of human grasp is the dual nature of forces applied in grasping and manipulation. Forces can be decomposed into external forces which equilibrate the forces and moments of a task and produce motions of the grasped object, and internal forces which stabilize the grasp.

In the work of Iberall, external and internal forces appear in the context of virtual fingers and oppositions. While we recognize the usefulness of virtual fingers for generalizing the taxonomy of Figure 1.1, our own interpretation is slightly different and therefore we have added "virtual finger" numbers to the revised taxonomy of Figure 1.1. The Opposed-Thumb (Grasps 6-9) and Lateral Pinch (Grasp 16) are two-fingered grasps since there are two independently controllable gripping surfaces. Even the Opposed Thumb-4 Finger grasp is basically a two-fingered grasp since the four fingers act in unison. At the other end of the spectrum, power grasps 1-3 and 11 are difficult to describe in terms of virtual fingers since they completely envelope the part with something approaching uniform radial symmetry, but have no independent contact areas. Finally, the non-clamping grasps (almost non-grasps) such as the Platform and Hook grasps have one virtual finger.

The relationships between virtual fingers and oppositions and the analytic concepts of internal and external grasp forces becomes clear with a simple example such as the Tripod grasp, as seen in Figure 1.7. Iberall classifies the Tripod grasp as a two-virtual-finger grasp with one opposition. In the past we have argued that because there are three independently controllable contact locations it is a three-virtual-finger grasp. However, from a practical standpoint, there are just two oppositions, both involving the thumb. The human hand has some coupling between the index and third fingers, and the magnitude of the internal grasp force between these

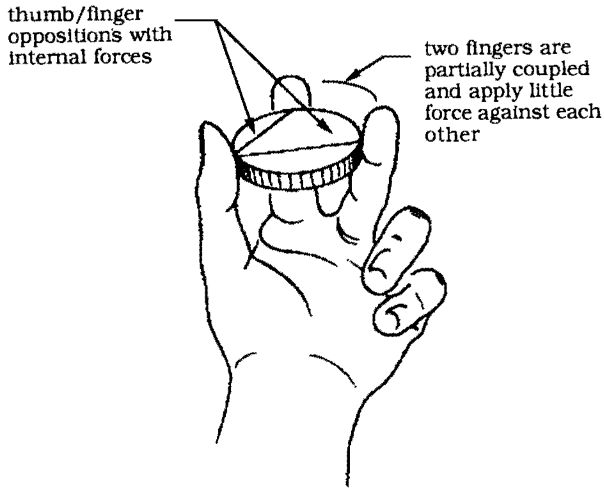

Figure 1.7: The Tripod grasp involves three independently controllable fingers but is dominated by two thumb/finger internal forces.

fingers is never large. The thumb is not just another finger with a special orientation, it is opposed to the fingers and thus can exert much larger forces against them. Moreover, if one examines the kinds of manipulations commonly done with a tripod grip it will be seen that the dominant axes of object motion are defined by moving the thumb up-and-down or side-to-side with respect to the fingers. In contrast, for the Stanford/JPL hand [Mason and Salisbury 1985] the tripod grasp becomes a 3-virtual-finger grasp with *three* opposition pairs, since all fingers are independent and nearly equal forces can be applied between each pair of fingers.

This suggests that virtual fingers correspond to independently controlled contact sites, and oppositions correspond to internal grasp forces. A tripod grasp may therefore have either two or three virtual fingers depending on the amount of coupling between the index and third fingers. In other words, the number of contact sites which *could* be independently controlled may be larger than the number actually used. (Of course, the number of contact sites which can be independently manipulated is also limited by the rigid body constraint of the object.)

The distinction between the number of virtual fingers and the number of opposition pairs (for those grasps where the numbers are different) speaks to the number of degrees of freedom required in the task and the amount of coupling among the fingers. This coupling is expressed analytically as off-diagonal terms in the grasp stiffness matrix [Cutkosky and Kao 1989].

1.5 Lessons for future analyses and for hand design and control

1.5.1 OBJECT REPRESENTATION AND GRASPING FEATURES

As mentioned earlier in describing the grasp taxonomy, approximate geometric descriptions of the objects (long, thin, disk-shaped, etc.) are too vague. A perspicuous representation would make reasoning about grasping easier and more effective. One key aspect is the designation of grasping "features." Features should not be neutral descriptions of the part geometry (e.g., cubes, cylinders) but should emphasize elements of the geometry that are important for grasping and task execution. Thus a hammer would be described largely in terms of its handle and the contact point on its head. With a feature-based description of objects, Grasp-Exp would ultimately resemble rule-based planning systems for setup and fixturing of machined parts, such as GARI [Descotte and Latombe 1984]. Feature-based descriptions of parts have also been explored for automatic robot grasp planning [Lozano-Pérez *et al* 1987; Popplestone 1987].

A proper object representation for grasping can be used not only in working with well-characterized tools and parts, but also with unknown objects in an unstructured environment. Stansfield [1988] has considered this problem in the context of grasping incompletely described objects whose shapes are determined by sensing. She uses a "spatial polyhedron" representation, which facilitates incorporation of new geometric information as it is sensed.

One important type of feature is possible grasp location. Following an earlier idea by Jameson [1987], Ji [1987] suggests algorithms for finding "double normals" on the surface of an object. Double normals are basically faces with opposed, collinear normals. Ji shows that double normals are good places for exerting and controlling the internal forces to maintain stability. In other cases, it is advantageous to position fingers symmetrically with respect to one of the ends of a double normal. Ji gives some heuristics for choosing possible grasp locations: for objects with parallel, planar faces position the contacts so that the contact normals are antiparallel; otherwise, position the contacts so that the inward pointing normals meet at a point. These double normals can also be thought of as candidate locations for the oppositions described by Iberall.

There are many important issues here which have yet to be explored. For example, how do we accommodate multiple task axes for a single tool? A screwdriver can be used to pry or stab in addition to turning a screw, and each task specifies a different principal axis. Also, objects can have several levels of detail, and it is not always clear which are unimportant. Thus a screwdriver handle is basically a cylinder, but has minor features such as ridges and knurls, which are important for applying torque.

The level of detail needed to describe an object may determine the fundamental approach to geometry. If the space of all object shapes can be

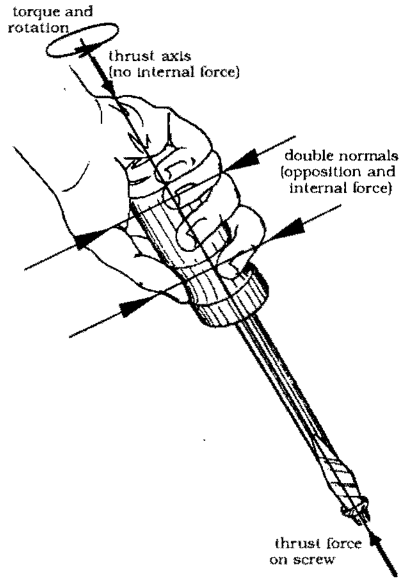

Figure 1.8: Principal task axes and double normals for turning a rusted screw.

represented by a small catalog of prototypes (or built from combinations of a few primitives) then it may be possible to use a rule-based approach. The question of object description also relates to the tactile sensing-based approach to finger placement. If exact finger placements can be determined on an ad hoc basis while grasping, then the grasp planner need only work with a rough prototype shape.

1.5.2 Relating object and task axes

When an object is used to perform certain tasks (e.g., turning a screw with a screwdriver) certain axes and features (e.g., an axis of rotational symmetry or a pair of opposed faces) tend to become most important. In this way, object geometry, in terms of features, can be correlated with the needs of a task.

Consider the screwdriver in Figure 1.8. The principal task forces include a moment about and thrust along the central axis, while the principal motion is a twist about the central axis. The magnitudes of the forces and motions on these axes dictate the choice of grasp. The tip is the action feature. The handle is the graspable feature. Following the grasp taxonomy, or the rules in Grasp-Exp, we would conclude that because the thrust force and torque are large, we need a power grasp. Because the handle is a thin cylinder, we choose a wrap. Finally, since the ability to apply twisting motions with the wrist is important (more important than tactile sensitivity, or the ability to apply radial forces or moments perpendicular to the tool axis) we choose Grasp 4.

From a more analytic perspective, we see that the tool handle is approximately axisymmetric and therefore has an infinite number of double normals in the radial direction. Applying internal forces across these double normals, we can resist thrust force and torque through friction. But if the required thrust force is large, as in trying to free a rusted screw, then friction on the handle will not suffice. In this case, we might look for a pair of double normals that involves the handle's end. But of course, there is no such pair. When the palm is used to apply a thrust force to the end of the handle the opposition is with the screw itself. Thus, there is no ability to independently control internal forces along the central axis; this is acceptable as long as the thrust force is predictable (e.g., the screw never suddenly pulls on the screwdriver). Looking at the same axis from a kinematic point of view, we observe that we do not have form closure along it.

As for the task motion, although we do not actually impart the twist with our fingers, we adopt a grasp that maximizes our ability to twist with the wrist. By contrast, if we use the same screwdriver for prying open the lid of a paint can we focus on an axis perpendicular to the central axis.

1.5.3 Hand design issues

In retrospect, the most useful contribution of the study of human grasps, from the standpoint of designing and controlling robot hands, has been a better appreciation of how task requirements and object geometry combine to dictate grasp choice. The study has resulted in a grasp taxonomy, which makes it possible to identify particular grasps and to trace how they derive from generic grasp types. The fact that both task requirements and geometry are important is clear from everyday experience. The grasp we use for picking up a pencil is entirely different from the one we use for writing, although the object geometry remains the same. On the other hand, if we consider the task of filing a machined part, the grasp we use for a flat file is different from the grasp we use for a round one, although the forces and motions are the same.

From the standpoint of hand design, we find that although the expert system contains a great deal more information than can be represented in a taxonomy, the taxonomy remains useful as a design aid since it allows one to see very quickly where a particular grasp resides in the space of possible grasps.

One fact that became clear in studying grasping in a manufacturing environment is that many grasps provide immobilization, while manipulation is performed by the wrist and/or arm. All of the power grasps fall into this category. Because the human arm has redundant degrees of freedom, the range of manipulation possible using the wrist and arm is quite large.

For these grasps the principal function of the fingers is to provide a large workspace for immobilization of the grasped object. Furthermore, the availability of this capability must influence grasp choice to a great extent. This observation leads to the question of what the proper role of the robot hand should be.

Unlike human arms, robot arms have excellent positional accuracy. But they also have comparatively few degrees of freedom and a large mass which limits their ability to control small forces at the hand. However, new manipulator designs can incorporate light weight wrists with redundant degrees of freedom. Does this mean that a passive gripper that can grasp a wide variety of workpieces is the solution for manufacturing environments? Perhaps not. We are successful in grasping and manipulation largely through our ability to reorient objects and modify grasps in response to shifting task requirements. This would obviously not be possible for a gripper capable of only immobilization grasps.

Another interesting aspect of the human grasping environment is the ubiquitousness of cylindrical handles, which are found on virtually every tool and many other objects as well. Our hands are clearly very good at grasping this shape, although this begs the question "Given the choice of any hand design, would another shape work as well?" A long, thin shape allows us to exert internal forces along a considerable axial distance, which permits us to resist torques about an axis perpendicular to the handle. Such moments are produced when forces are applied to the tool at some distance from the grasp region (e.g., in using a tennis racket). Many tasks produce just these sorts of moments in the hand. Hand surgeons have also noted that for a workman, the loss of the little finger can be more of a handicap than the loss of the ring finger, because of the decreased ability to resist such moments.

It is also possible to examine industrial gripper design in light of the taxonomy in Figure 1.1. For the most part, today's commercial grippers achieve particular instances of the power grasps on the left hand side of Figure 1.1. Increasingly, however, general-purpose grippers are inadequate for the variety of part shapes and tasks encountered in flexible manufacturing systems. A common solution is to provide an array of special-purpose grippers for each part style. The taxonomy in Figure 1.1 suggests, however, that if several grippers are to be used, they should be designed for classes of grasps and tasks – not for different part styles. To design a gripper for a part style is to design a tool, not a hand. Thus, like a phillips-head screwdriver which can only be used with phillips-head screws, the gripper is a special-purpose device.

A better approach is to start with basic task requirements and let those requirements dictate the design. For example, one might construct a gripper for precision grasps with opposed fingers and a second gripper for power wrap grasps. Another possibility is to construct a hand for two types of tasks with a single object. For example, a manufacturing hand used for picking up small power tools and then working with them could shift between the Opposed Thumb-4 Finger grasp, Grasp 6, and the Light Tool grasp, Grasp 5. Such generic designs can be adjusted to fit a variety of part shapes and finger adaptors may be used for specific constraints encountered with exceptional parts.

It is also unnecessary to achieve all of the different grasps in the taxonomy. For example, pulling on a wrench as shown in Figure 1.5 could easily be achieved with a wrap grasp. While it suits the machinist with his human hand to use a full repertoire of grasps, this Hook grasp may be unnecessary for a robot. In designing a robot hand and controller for a particular environment, the set of necessary and sufficient grasps can be determined from the taxonomy, and the capabilities of the robot gripper system can be matched to this set. In this way the grasp taxonomy can streamline hand design, construction, and control. Thus, in a form-follows-function sense, robotic hands can be made competent but not over-designed and hence overly expensive and difficult to use.

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