On Grasp Choice, Grasp Models, and the Design of Hands for Manufacturing Tasks

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Abstract—**Current analytical models of grasping and manipulation with robotic hands contain simplifications and assumptions that limit their application to manufacturing environments. To evaluate these models, a study was undertaken of the grasps used by machinists in a small batch manufacturing operation. Based on the study, a taxonomy of grasps was constructed. An expert system also was developed to clarify the issues involved in human grasp choice. Comparisons of the grasp taxonomy, the expert system and grasp quality measures derived from the analytic models reveal that the analytic measures are useful for describing grasps in manufacturing tasks, despite the limitations in the models. In addition, the grasp taxonomy provides insights for the design of versatile robotic hands for manufacturing.**

I. Introduction

As MULTIFINGERED robotic hands begin to appear in research laboratories, the design, analysis, and control of such hands has become an active area of research. Numerous analytic approaches have been proposed for characterizing grasps and modeling the process of manipulation. In addition, there have been significant advances in control strategies and tactile sensing for hands. Yet it seems that we are still a long way from building robots that can independently decide how to pick up and manipulate objects to accomplish everyday tasks. Part of the problem is that since hands and manipulation are complex, attempts to model them require simplifying assumptions not usually valid outside of carefully structured experiments in the laboratory. Consequently, we were lead to compare analytic grasp models with the processes that people use in choosing grasps and manipulating tools and workpieces in a particular environment.

The work addresses a number of basic questions:

- Can an order be imposed on human grasp selection and can the process be codified?
- How limiting are the assumptions made in today's analytic grasp analyses and are the resulting grasp quality measures practical?
- How does human grasp selection compare with the analytic approaches?
- Are the results of studying human grasp selection useful for the design of robot hands and for automating robotic grasp selection?

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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 (e.g., forces) 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.

Our study of manufacturing grasps focused on tasks in *small-batch machining operations, or job-shops. Small-batch* machining is an increasingly important component of manufacturing (roughly 75 percent of machined items are produced in batches of 50 parts or fewer [18]) and has spurred considerable work on flexible, automated machining systems. Where traditional small-batch operations counted on human operators to adapt to minor variations in parts, fixtures, and processes, automated systems rely on sensors, robots, and computers. Unfortunately, the adaptability of human operators has been difficult to duplicate, especially in handling, assembling, and fixturing parts and tools. Thus it is common today to see operations in which CNC machine tools cut parts but humans fixture the parts on pallets and perform numerous tasks using hand tools to assemble, inspect, and finish parts and fixtures.

The study of grasps was confined to single-handed operations by machinists working with metal parts and hand tools.[1] 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 [4]. In subsequent work, a grasp expert system has been developed, using the original results and taxonomy as a starting point. The purpose of the codification exercise was not to develop a program to predict what grasp a human would adopt under particular circumstances (although it now appears that this can be done in a limited context) but to have a running, testable framework in which to try out hypotheses. In

[1] However, we observe that two-handed tasks often use the same grasps as found in our one-handed taxonomy, presented in Fig. 4.

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addition, the codification exercise forces one to be more careful about defining terms and organizing information. While the expert system is not yet, and probably never will be, complete (after all, how useful is an expert system that tells us how we grip things?) it has forced a closer look at how grasps are chosen and has resulted in modifications to the original taxonomy in [4]. The codification exercise has also lead us to explore patterns or sequences among grasps, which provide insights for controlling robotic hands to manipulate parts.

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

In the following sections, we briefly review analytic grasp models and examine the assumptions upon which these models rest. We then present the results of our study of human grasp selection in manufacturing tasks and describe the grasp expert system that grew out of the study. Finally, we discuss the results of the study and codification exercise in terms of their ramifications for designing manufacturing hands.

II. Analytic Approaches to Grasp Modeling and Grasp Choice

A. Grasp Modeling

As Fig. 1 indicates, manipulation is complex, typically involving combinations of open and closed kinematic chains, nonholonomic 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., [1]) 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
- linearized (instantaneous) kinematics
- quasi-static analysis (no inertial or viscous terms)
- no sliding or rolling of the fingertips
- no cases with redundant degrees of freedom and no overconstrained grasps.

Recent analyses, such as those by Nakamura *et al.* [19], Cutkosky and Wright [5], Ji [11], and Li and Sastry [14], 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, ignoring elasticity, backlash, and friction
- simplified representations of the grasped objects, typically treating them as smooth, rigid geometric primitives or polyhedra.

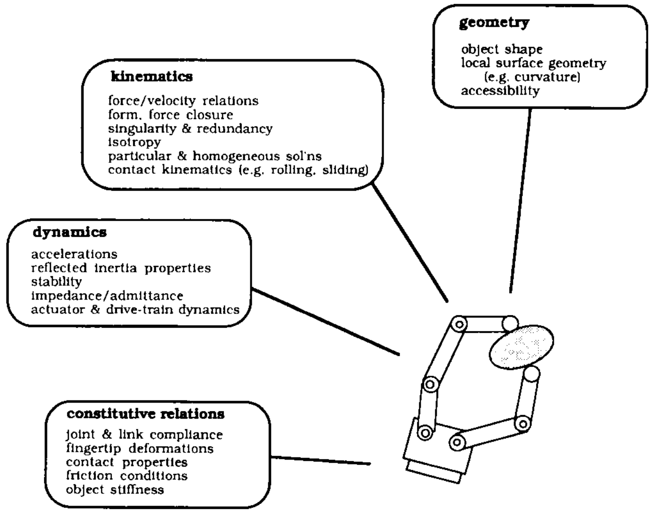


Fig. 1. Issues in analytic modeling of grasping and manipulation.

Based on the various analytic models of grasping and manipulation, a number of quality measures have been developed. For reference, these are summarized in Table I. We will return to the measures in Section V and compare them with the empirically derived "grasp attributes" used in the grasp expert system.

While the measures in Table I describe the properties of a grasp, and are useful for assessing the suitability of a grasp for a given task, 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 and the work space of the hand. Thus a number of investigators have proposed geometric criteria for automated grasp selection [2], [15], [28].

B. Analytic Grasp Choice

The problem of choosing a grasp, based on analytic grasp models, quality measures, and constraints, is illustrated in Fig. 2. 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 I (along with additional geometric issues) should be included in the objective function, and which should be used as constraints. Kerr and Roth [12] 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 *et al.* [19] search for a grasp that minimizes internal forces (and consequently, grasping effort)

TABLE I
DEFINITIONS OF ANALYTICAL MEASURES USED TO DESCRIBE A GRASP

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 [6].
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 [17]?
Force closure	Assuming that external forces maintain contact between the fingers and the object, is the object unable to move without slipping when the finger joints are locked? Formally, a grasp satisfies force closure if the union of the contact wrenches has rank 6 [17], [22].
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 unisense contact twists is a null set. Thus seven frictionless point contacts are in general required to achieve form closure on a rigid body [13], [17].
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 [12], [17]. Li and Sastry [14] define similar grasp quality measures that are functions of the singular values of the grasp Jacobian.
Internal forces	What kinds of internal grasp forces can the hand apply to the object? 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 grasp equilibrium [12], [17].
Manipulability	While not consistently defined in the literature, a useful definition is: Can the fingers *impart* arbitrary motions to the object? Thus a manipulable grasp must have force closure and a connectivity of 6. In addition, the rank space of velocities due to the finger joints must span the space of velocities transmitted through the contacts [12].
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 [5], [10]–[12].
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 [6], [21]. At higher speeds, *dynamic* stability must be considered [19].

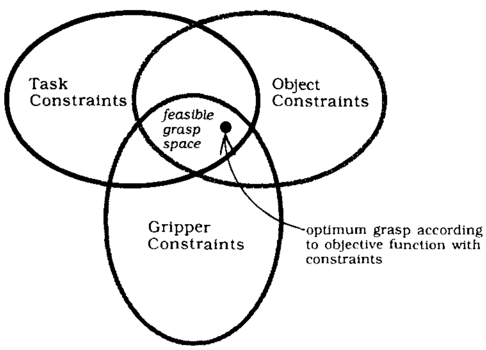


Fig. 2. Choosing a grasp that maximizes an objective function subject to task, object, and gripper constraints.

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 [24], [29]. In a very different approach, Jameson and Leifer [10] 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 [14] 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.

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. However, Ji [11] outlines a sequence in which the first step is to find "grasp planes" containing grasps that satisfy form closure and have the ability to control internal forces. Next, 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 [14].

As we review the competing approaches in the literature, and examine the serious simplifications upon which they rest, we are lead to wonder how useful the analytic approaches to grasp choice can be outside of carefully controlled laboratory experiments. To be fair, any of the models may be a reasonable approximation for a particular set of tasks. Thus while point-contact is a poor approximation when human fingers hold a small object, it is a fair approximation as long as the contact areas are small compared to the characteristic length of the object [5]. Nonetheless, we are motivated to look at some actual manufacturing tasks and the characteristics of the grasps adopted to accomplish them.

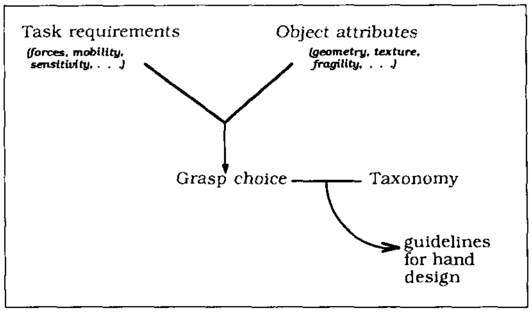


Fig. 3. Task requirements and object attributes combine to dictate the grasp choice. Viewing the grasp as part of a taxonomy permits us to draw conclusions about designing robotic hands.

III. Exploring the Human Grasp Selection Process

If robot hands are going to succeed in small batch manufacturing they will have to display some of the same adaptability and sensitivity that human hands do. Thus it is useful to analyze human grasps in machining, not necessarily to imitate them, but to understand the relationship between task requirements and the grasping "solution" adopted to meet those requirements. This philosophy is summarized in Fig. 3. Of course, we have to be careful in drawing conclusions based on a study of human hands. The hand has evolved over millions of years as an organ used as much for sensation and communication as for manipulation. In fact, for many manufacturing tasks the human hand is less than ideal. When a mechanic starts to work on a machine, the first thing he reaches for is his toolbox, with pliers, wrenches, tweezers, and work gloves to help him finish the job. This suggests that by understanding the grasping and manipulation requirements for tasks in a specific environment it should be possible to design a hand that *exceeds* human performance.

A. Previous Explorations of Human Grasps

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 [19] and summarized by Taylor and Schwarz [27]: *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, as the pencil example cited earlier illustrates, 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 suggests that grasps should first be categorized according to function instead of appearance.

Napier [20] suggests a scheme in which 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.

In the following section we begin with the two basic categories suggested by Napier [20] and develop a hierarchical tree of grasps. As one moves 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 a central role in determining the grasp.

B. A Taxonomy of Manufacturing Grasps

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 Fig. 4, 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 *nonprehensile* 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 Figs. 4 and 5. For example, if 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 15 in Figs. 4 and 5) will probably be used. If the object has a compact or approximately spherical shape then Grasp 11 is most likely. If the object is prismatic (i.e., a long shape with nearly constant cross section, such as a cylinder or a hexagonal prism), then a wrap is chosen. Since many objects, including the handles of most tools, have prismatic shapes, the power wrap represents a large family of manufacturing grips.

Fig. 6 shows several precision grasps from the right side of the taxonomy. 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 using the thumb and four fingers as in Grasp 6, or it can be gripped by one end, like the hollow cylinder shown for Grasp 12 in Fig. 6.

C. Trends in the Taxonomy

Moving from left to right in Fig. 4, 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

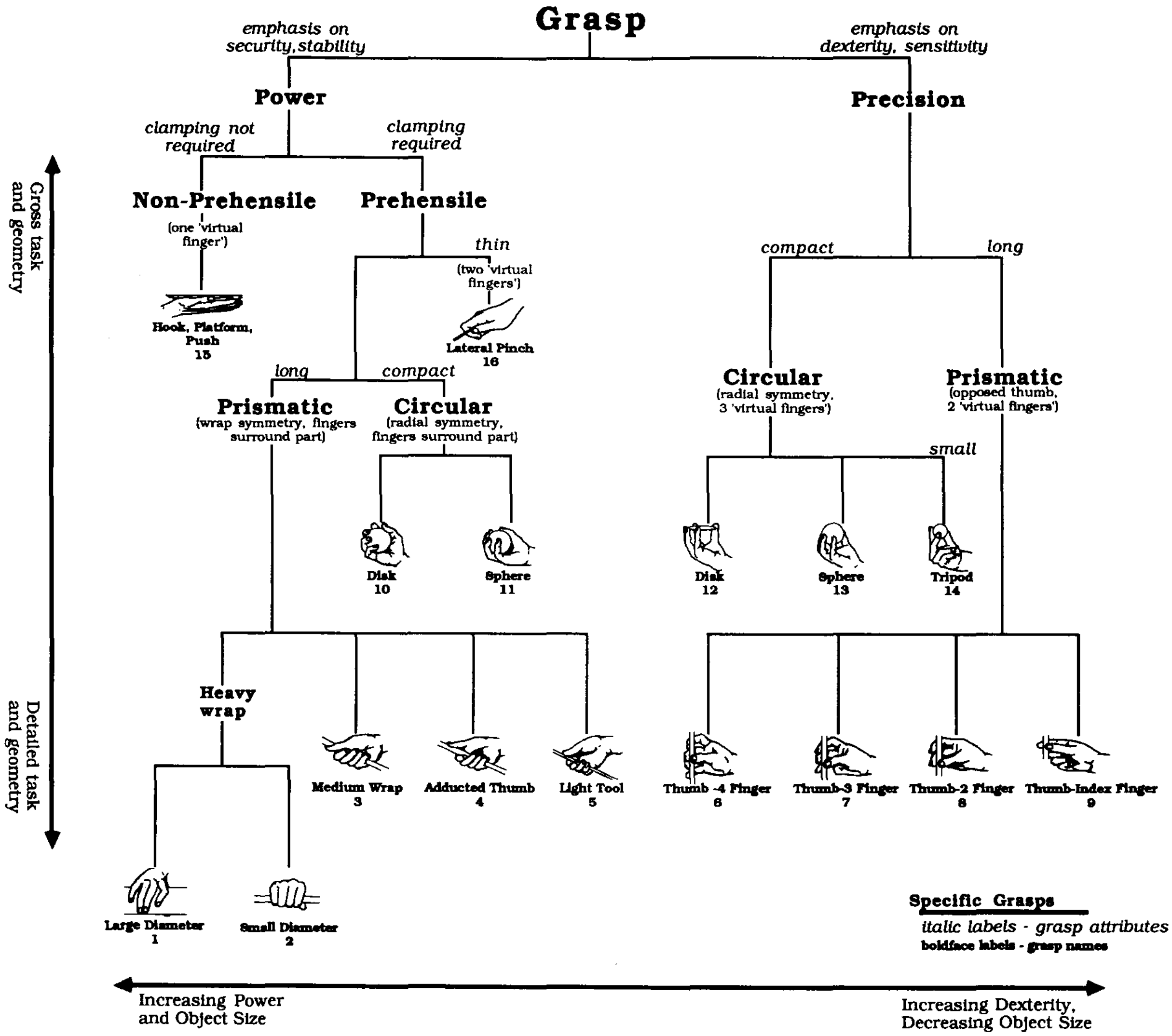


Fig. 4. A partial taxonomy of manufacturing grasps, modified from a taxonomy presented in [4]. The drawings of hands were provided by M. J. Dowling and are reprinted with permission of the Robotics Institute, Carnegie-Mellon University.

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, the trend is from general task considerations, such as whether clamping is required, to details of geometry and sensing. Again, the trend is not strictly observed. For example, a small, flat object may provoke the choice of a Lateral Pinch grip near the top of the tree.

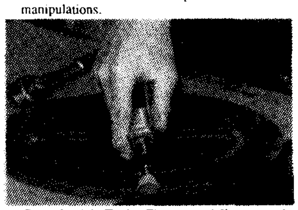
The role of task forces and torques on grip choice is most apparent when the hand shifts between grips during a task. For example, in unscrewing a knob the hand shifts from Grasp 11 to Grasp 13. Similarly, when holding a tool, as in Grasp 3, the hand shifts to Grasp 5 as the task-related forces decrease and may adopt Grasp 6, a precision grasp, if the forces become still smaller. 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 IV, is that sequences can be traced in the taxonomy, corresponding to adjustments that the machinists make in response to shifting constraints.

D. Limitations of the Taxonomy

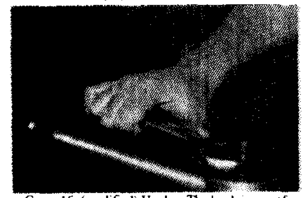
While the taxonomy in Fig. 4 has proven to be a useful tool for classifying and comparing manufacturing grasps, it suffers from a number of limitations. To begin with, it is incomplete. For example, there are numerous everyday grasps, such as the grasp that people use in writing with a pencil or in marking items with a scribe (Figs. 7 and 8) that are not included. It was also found that the machinists in our study adopted numerous variations on the grasps in Fig. 4, 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 individual grasps could usually be identified as "children" of the grasps in Fig. 4. To examine such issues further, and to clarify the roles of dexterity, sensitivity and stability in grasp choice, an expert system was constructed for choosing grasps from initial information about the task requirements and object shape.

Grasp 2: Heavy Wrap -- Fingers and palm wrap around a heavy object. Friction provides much of the force balance. Here, loading a lathe chuck is a heavy peg-in-hole assembly task using compliance and force feedback. The wrist performs fine manipulations.

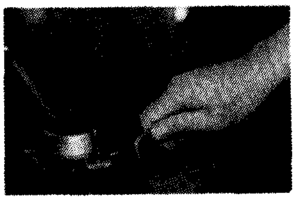
Grasp 3: Medium Wrap -- Fingers and thumb curl about a tool. The object is smaller and lighter than in Grasp 2 at left, but task and grip forces are high. Large motions are made with the arm and fine motions with the wrist. The thumb may be adducted (Grasp 4) for control of the tool tip.



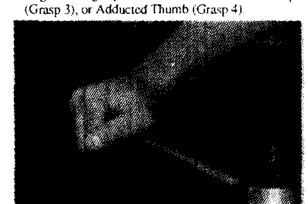
Grasp 5: Light Tool -- Fingers partially surround the object, but there is also tip prehension. This is a power grasp since the fingers do not manipulate the part, but has some attributes of precision grasps: good tactile sensitivity and an ability to adjust the grasp stiffness.



Grasp 15: (modified) Hook -- The hook is one of a class of one-sided "grasps" (a pure hook would not use the thumb as shown here) that includes a waiter's platform for supporting a tray. Forces are largely in one direction. A hook in which the fingers are tightly curled becomes a Medium Wrap (Grasp 3), or Adducted Thumb (Grasp 4).



Grasp 16: Lateral Pinch -- A thin object is clamped between the thumb and side of the index finger. Task and grasp forces are high. This grasp is used to turn a key in a lock and is closest to the grip achieved with 2-finger industrial grippers.

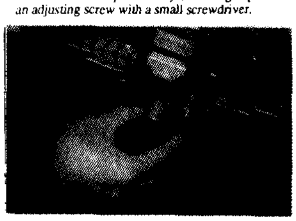


Grasp 11: Power Sphere -- Fingers, palm and thumb surround the compact part in a non-directional power grasp. Friction accounts for much of the force balance.

Fig. 5. Several power grasps used in a small-batch machining environment. Grasp numbers match the numbers in Fig. 4.

Grasp 6: Opposed Thumb - 4 Finger -- A precision grasp for long objects. Fingertips and thumb manipulate the part, with best control in rolling it about its axis. A person may use this grasp to turn an adjusting screw with a small screwdriver.

Grasp 9: Opposed Thumb-Index Finger -- A grasp for small objects. Finger and thumb manipulate the part, with high mobility along two axes. Fingertips conform to and partially entrap the part. Grasps 6-8 and 12-14 converge to this grasp as the object cross section becomes small.



Grasp 12: Precision Disk -- A radially symmetric grasp with the fingertips. Fingers can adjust orientation of the part, but larger twisting motions are made with the wrist. Grasp 10 will converge to this grasp as required torque decreases.

Grasp 14: Tripod -- The "classic" grasp of 3-fingered dextrous manipulation. The three most independent fingers are used, with resulting mobility in all directions.

Fig. 6. Several precision grasps used in small-batch machining. Grasp numbers match the numbers in Fig. 4.

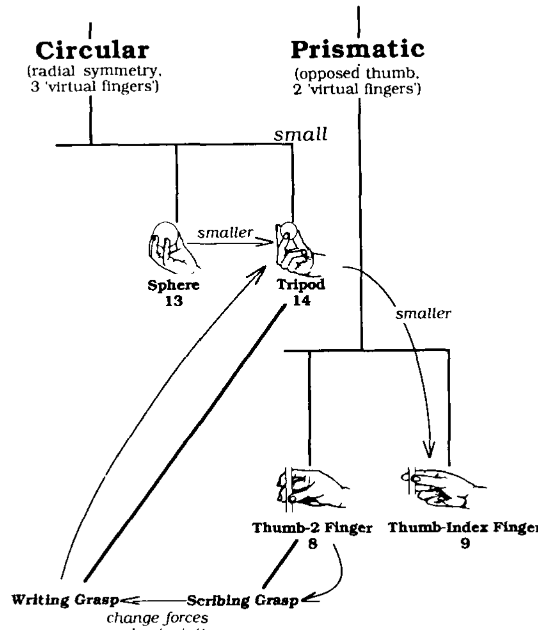


Fig. 7. Trends in the grasp taxonomy.

IV. Grasp-Exp: An Expert System for Manufacturing Grasps

An object-oriented expert system provides features not found in a tree-like taxonomy. For example, it allows individual "child" grasps to inherit the properties of more than one parent. It also makes it possible to assign a combination of qualitative and quantitative attributes to grasps so that comparisons may be made with the analytic grasp measures discussed in Section II. More importantly, the expert system makes it easy to consider extra constraints (e.g., only three fingers will fit on the handle of a particular tool) and to ask "what if" questions (e.g., "what if I only had three fingers and could not oppose my thumb?").

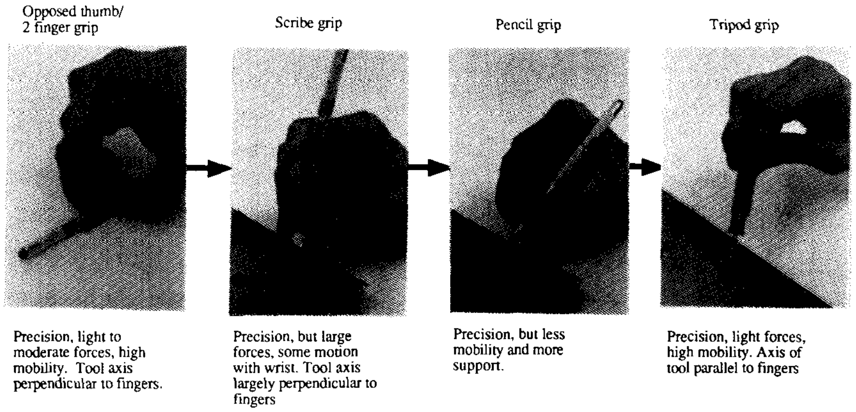


Fig. 8. A sequence of grips in response to changing task requirements.

An expert system, Grasp-Exp, was written in POGIE,[2] a framework developed by K. Ishii for his work on knowledge-based design of mechanical systems [9]. POGIE is written in Common Lisp and supports forward and backward chaining, numerical values, and fuzzy measures. The basic syntax of statements in POGIE is predicate logic: the system (e.g., to associate numerical values with the grasp sensitivity) without affecting the syntax of many rules. In fact, some care is required in defining grasp attributes. For example, the easiest way to identify a precision grasp would be to ask whether the fingers actively manipulate the part or tool—but this is hardly fair, since part of the grasp choice

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(Rule 37
(if (grasp is precision-grasp)                 ;IF the grasp is a precision grasp
  (*provable (requires object-size small) fail) ;AND the object is not small
  (requires rough-object-shape compact))       ;AND the object has a compact shape
(then (grasp is precision-circular-grasp)))    ;THEN the grasp is a "precision circular grasp"
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It is also straightforward to include numerical criteria in POGIE:

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(Rule 07
(if     (requires stability $num)              ;IF the grasp requires a stability rating
        (*>$num 0.75 t)                        ;of greater than 75%
        (requires security $num)               ;AND a security rating
        (*>$num 0.75 t)                        ;of greater than 75%
(then (grasp is power grasp)))                 ;THEN the grasp is a "power grasp"
```

Several versions of Grasp-Exp were developed as we experimented with different approaches to interacting with the user and presenting information about the task and the grasped object. The first attempt was to put the rules for grasp selection directly into the framework that Ishii had developed for interactive systems design. A procedural front-end would ask questions of the user and record the answers in a list of facts. Grasp-Exp would then try to draw conclusions about the grasp. Unfortunately, the question-asking procedure tended to ask unnecessary questions which irritated users. For example, the system might ask about the delicacy of touch required for a "heavy wrap" grasp. In addition, we had not distinguished carefully between *grasp-types* and *grasp-attributes* in the knowledge base. The *grasp-type* is the classification in the taxonomy. For example, *heavy-wrap-grasps* are a subset of *wrap-grasps*, *prehensile-grasps*, and *power-grasps*. The *grasp-attributes* are the characteristics required of the grasp (e.g., sensitivity, stability), established by interrogating the user. As a result of this confusion, it was difficult to modify

[2] Portable Generic Inference Engine.

exercise is to decide whether the object can be manipulated with the fingers or whether it should be manipulated with the wrist.

The latest version of Grasp-Exp has the structure shown in Fig. 9. The user begins by entering any number of facts about the grasp; for example, that the grasp requires large forces and involves a large, cylindrical workpiece. The initial facts are then acted upon by the Grasp-Exp in either a forward chaining or backward chaining mode. In the former mode, the system tries to prove that one or more of the individual grasps will satisfy all the requirements, and in the latter mode, Grasp-Exp uses the initial facts to trigger rules. In either case, Grasp-Exp asks questions only when it cannot prove or deduce further results without additional information. However, due to the branching nature of the taxonomy, backward chaining is more efficient. Thus when trying to "prove" that a grasp might be manipulated with the fingers the system chains backward, looking for supporting evidence (e.g., are the part and the task forces relatively light? how important is sensitivity? etc.). In this way, Grasp-Exp has become closer to the classic consultant who lets the user lay out some initial facts and then

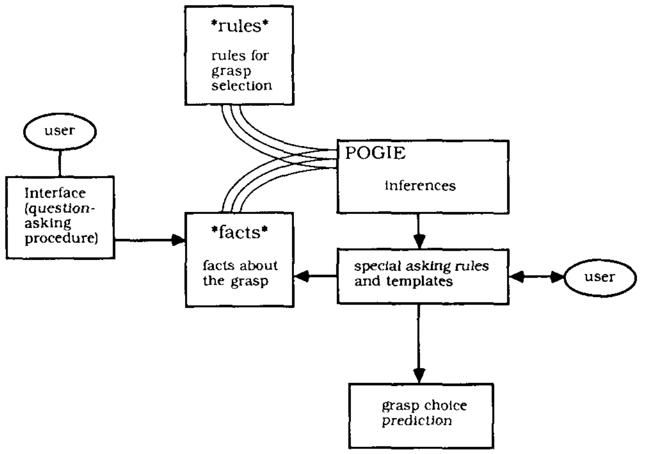

Fig. 9. The architecture of Grasp-Exp.

```
(WHAT IS THE DEXTERITY REQUIREMENT ? SELECT FROM (YES NO UNKNOWN))
>no

(WHAT IS THE STABILITY REQUIREMENT ? SELECT FROM (YES NO UNKNOWN))
>yes

(HOW IMPORTANT IS SECURITY IN YOUR GRASP? SELECT FROM
 ([0 TO 1] UNKNOWN))
>0.7

(WHAT IS THE CLAMPING REQUIREMENT ? SELECT FROM (YES NO UNKNOWN))
>yes

(WHAT IS THE OBJECT-THICKNESS REQUIREMENT ? SELECT FROM
     (THIN NOT-THIN))
>not-thin

(WHAT IS THE OBJECT-SIZE REQUIREMENT ? SELECT FROM
     (SMALL MEDIUM LARGE UNKNOWN))
>medium

(WHAT IS THE ROUGH-OBJECT-SHAPE REQUIREMENT ? SELECT FROM
     (COMPACT PRISMATIC UNKNOWN))
>compact

(WHICH OF THE FOLLOWING IS CLOSEST TO THE SHAPE OF THE OBJECT? SELECT
     FROM
 (SPHERE DISK RECTANGLE CYLINDER UNKNOWN))
>disk

REQUIRED GRASP is of type: POWER DISK-GRASP [GRASP 10]

Other classifications are as follows:

    POWER-GRASP
    PREHENSILE-GRASP
    PENTADACTYL-GRASP
    CUPPED-GRASP
    DISK-GRASP
```

Fig. 10. A short session with Grasp-Exp—answering with "unknown" would have caused Grasp-Exp to ask more detailed questions.

tries to form conclusions or diagnoses, asking questions along the way. Fig. 10 shows a short session with Grasp-Exp.

While Grasp-Exp is still unfinished (there are currently about 50 rules specifically involved in grasp choice, along with lists of templates for object-attributes and grasp-attributes), it seems that a total of about 100 rules would be adequate for predicting how people will grasp parts and tools in a particular environment. As discussed in the following section, most of the additional rules would make Grasp-Exp more "friendly" in interrogating the user and would permit more detailed descriptions of the task and the grasped object.

A. Lessons from Grasp-Exp

Grasp-Exp's knowledge of the factors involved in human grasp choice is far from complete. Indeed, Grasp-Exp may never be complete, for the point of constructing Grasp-Exp was not to create a reliable predictor of how humans will grasp tools or parts but to raise and clarify additional issues in the study of manufacturing grasps. In this section, we discuss a number of the issues that surfaced during the work on Grasp-Exp.

First, it is necessary to quantify terms like "precision," "dexterity," and "sensitivity" so that different grasps may be ranked. For example, the left branch of the grasp taxonomy in Fig. 4 includes power grasps that "emphasize security, stability." But must a grasp manifest both security and stability to qualify or will either one do? Further, suppose that a grasp has stability and security, but also displays some sensitivity to vibrations? After some experimentation, it was decided that there were scales of dexterity, sensitivity, power, and stability such that precision grasps tend to be at one end of the spectrum and power grasps at the other. For example, the Light Tool Grasp (Grasp 5) is distinguished from other power wraps primarily by the ability to sense forces and vibrations (a characteristic of precision grasps) although it is classified as a power grasp because the fingers and palm surround the part and do not manipulate it. As another example, the precision Thumb-Index Finger grasp (Grasp 9) has some of the characteristic stability of a power grip since the soft fingertips partially encompass a small object.

Assigning quantities to terms like dexterity and sensitivity is not easy. Thus it was necessary to have the expert system ask additional questions about the force requirements, approximate object weight, the importance of sensing vibrations at the tool tip, and so forth, so that the relative importance of stability and dexterity could be assessed. 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? ..." A related difficulty with Grasp-Exp, common to many expert systems [30], is the need to quantify subjective terms like "heavy," "large," and "thin." Clearly, it is necessary to be consistent in using such terms; yet, people are uncomfortable with assigning numerical values. For example, if the system asks for the object size (small, medium, large), how small is "small?" As in assigning measures of dexterity and precision, the solution lies in asking different questions, e.g., "is the object smaller than your fist?" In fact, this is the best way to ask such questions because it is really the *relative* size of the object with respect to the hand that matters.

In experimenting with Grasp-Exp it also became clear that the very approximate geometric descriptions (compact, thin, prismatic) in the taxonomy were too vague. These descriptions were extended to include the *rough-object-shape* and detailed object shape so that one could ask whether objects were long, thin, disk-shaped, rectangular, and so forth. Although not currently implemented, Grasp-Exp should be working with geometric *features* of the parts and tools, stored in a database. The 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. Thus a cup or a hammer would be described largely in terms of its handle. 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 [7]. Feature-based descriptions of parts have also been explored for automatic robot grasp planning [15], [23]. Finally, in addition to describing the shapes and grasping features of parts, Grasp-Exp should be extended to understand the details of the part orientation with respect to the hand; for example, the orientations of the principal axes of a tool with respect to the fingers.

Experiments with Grasp-Exp also revealed sequences among the grasps in the original taxonomy. As a person proceeds with a task, the grasp shifts in response to changing force/torque requirements or geometric constraints. For example, consider pulling hard on the handle of a wrench to loosen a large bolt. Initially, the Hook Grasp (a subgrasp under Grasp 15) may be used for maximum pulling force. But as the bolt starts to loosen, and the required force on the handle is less predictable, the hand switches to a Medium Wrap (Grasp 3) or Adducted Thumb grasp (Grasp 4), in which the fingers entrap the handle to keep it from slipping. As the following, slightly more complicated example reveals, subgrasps (one level below those shown in the taxonomy) may not have a single parent. A person picks up a pen or a scribe and starts to mark with it, bearing hard upon the writing surface. Upon finding that it is not necessary to press hard, the person shifts to a more standard writing grasp. As the task is completed, the person shifts to a tripod grasp using the scribe as a pointer to indicate the markings to a colleague. The sequence involves a progression of grasps from Grasp 8 to Grasp 14. Grasp 8 is useful for picking up an object. Mobility is mostly confined to rolling the object about its central axis. The grasp choice is dictated largely by the need to lift the object from a flat surface; any of the other opposed-thumb grasps would also suffice. The Scribing Grasp involves a shift of the fingers to produce larger forces and to orient the axis of the scribe slightly more parallel to the fingers so that mobility in rolling the object is reduced but mobility perpendicular to the object axis is increased. The Writing Grasp further shifts the object axis so that it becomes parallel with the fingers resulting in slightly greater mobility, at the expense of force. Finally, the Tripod can be seen as a Writing Grasp in which the hand has slid to one end of the object (losing support from the side of the palm) so that mobility is improved in all directions, but only small forces can be applied.

V. Discussion

In summarizing the results of the study of one-handed manufacturing grasps, we return to the questions raised in the introduction:

1) Can the human grasp process be codified? Under limited circumstances it now appears that an expert system can predict how people will grasp parts and tools. Moreover, in experiments with Grasp-Exp 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.

2) How accurate are the analytic models of grasps, with their numerous simplifications? Under particular circumstances, any one of the analytic grasp models may be a good approximation. 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 [5] more accurately approximates the Tripod and Thumb-Index Finger precision grasps, where the finger pads conform to, and even partially entrap the object. 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 limitations to the grasp.

3) How does human grasp selection compare with the analytic measures? In terms of the analytic measures discussed in Section II, the power grasps are stiffer, more stable, and have a larger resistance to slipping than the precision grasps. In addition, the power grasps for which clamping is required are form-closure grasps (assuming extra contact wrenches due to friction). The nonclamping grasps (Grasps 15) are force-closure, provided that external forces do not cause the fingers to detach from the object. Finally, the power grasps have a connectivity of 0 since the fingers do not manipulate the part. Like the power grasps, the precision grasps satisfy form and force-closure. However, the connectivity between the grasped object and the hand is always 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, consider the following grasp attributes and corresponding analytic measure (see Fig. 11):

- Sensitivity—A term that depends on many factors but is primarily related to how accurately the fingertips can pick up 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 more compliant grasp is more sensitive to small changes in force).
- Precision—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—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 work space of the hand.
- Stability—When people speak of a stable grasp they include both the definition in Section II, 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—In common use, grasp security is related to stability, but is most closely associated with resistance to slipping.

4) Are the results of studying human grasps useful for the design of robot hands? For designing robot hands, we need to turn from the details of human grasp choice to a general consideration of how grasps satisfy geometric and task requirements. For this purpose, we have found that although the expert system contains more information and is more flexible than the taxonomy, the taxonomy is more useful as a design aid since it allows one to see very quickly where a set of

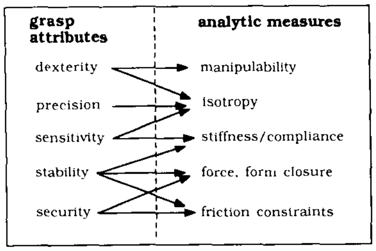

Fig. 11. Human grasp attributes in terms of analytic grasp measures.

grasps lies in the space of all possible grasps and to see how a specific grasp descends from the generic grasp types.

An effective way to extend the grasp taxonomy is to consider grasps in terms of "virtual fingers" that do not necessarily have a one-to-one correspondence with fingers of the human hand [8], [16]. Iberall [8] argues that in most grasps the object is held between two virtual fingers and that the type of opposition (e.g., trapping an object between the fingers and the palm, or between the pads of the thumb and the index finger) is of central importance. Iberall therefore recognizes three basic type of grasps:

1) encompassing grasps (grasps with palm opposition)—Grasps 1–4 and 11 are the most obvious examples of encompassing grasps;
2) lateral grasps (grasps with side opposition)—the Lateral Pinch, Grasp 16, is a grasp with side opposition;
3) precision grasps (grasps with pad opposition)—the precision grasps on the right-hand side of the taxonomy display pad opposition.

Iberall provides a table mapping the original taxonomy of Cutkosky and Wright [4] to her categorization of grasps with two virtual fingers. While we recognize the usefulness of virtual fingers for generalizing the taxonomy of Fig. 4, our own interpretation is slightly different and therefore we have added "virtual finger" numbers to the revised taxonomy of Fig. 4. 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. However, the disc and tripod grasps are more accurately thought of as grasps with three virtual fingers since they have three independently controllable contacts—three points define the object orientation. 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 nonclamping grasps (almost nongrasps) such as the Platform and Hook grasps have one virtual finger.

It is also possible to examine industrial gripper design in light of the taxonomy in Fig. 4. For the most part, today's commercial grippers achieve particular instances of the power grasps on the left-hand side of Fig. 4. For example, a two-fingered parallel-jaw gripper (Fig. 12(a)) is capable of pushing objects (a subcategory under Grasp 15) and of a grasp that resembles the Lateral Pinch (Grasp 16), in which a small object is clamped securely between two strong fingers. As another example, the commercial gripper of Fig. 12(b) is capable of Power Wrap Grasps (Grasps 1–3).

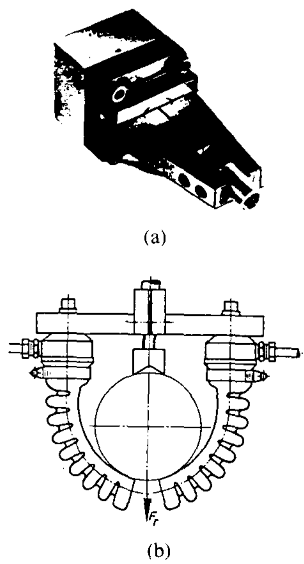

Fig. 12. Industrial grippers in terms of the grasp taxonomy. The typical two-fingered gripper in (a) (reprinted from Com-Pick Grippers [3]) executes the equivalent of a Lateral Pinch. The pneumatic gripper in (b) (reprinted from [26]) has a "palm" and is designed for wrap grasps. By contrast, most dextrous robotic hands are designed for precision grasps with three independent fingers.

Increasingly, general-purpose grippers are becoming 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. Although this method leads to difficulty in routing power and sensory information from the fingers through connections into the robot arm, and increases cycle times as grippers are swapped, it is attractive to manufacturing engineers since the grippers can be much less complicated than a universal hand. The taxonomy in Fig. 4 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 Fig. 4. For example, the task shown in Fig. 6 for Grasp 12 could easily be achieved with just three fingers, as in Grasp 14. While it suits the machinist with his human hand to bring out a full repertoire of grasps, Grasp

12 may be unnecessary for a robot. Similarly, the hammering task shown in Fig. 5 for Grasp 3 could be achieved with Grasps 2 or 4. From such observation, it is expected that a grasp taxonomy will allow the streamlining of hand design, construction, and control. Thus in a form-follows-function sense, robotic hands will be capable of a specified and necessary subset of tasks in a small-batch manufacturing cell but will not be overdesigned and hence overly expensive.

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References

[1] H. Asada, "Studies on prehension and handling by robot hands with elastic fingers," Ph.D. dissertation, Kyoto University, Apr. 1979.

[2] R. C. Brost, "Automatic grasp planning in the presence of uncertainty," *Int. J. Robotics Res.*, vol. 7, no. 1, pp. 1–17, 1988.

[3] Compact Air Products Inc., "Com-pick grippers," in *Catalog SC100*, Westminster, SC, 1983.

[4] M. R. Cutkosky and P. K. Wright, "Modeling manufacturing grips and correlations with the design of robotic hands," presented at the IEEE Int. Conf. on Robotics and Automation, San Francisco, CA, Apr. 1986.

[5] ——, "Friction, stability and the design of robotic fingers," *Int. J. Robotics Res.*, vol. 5, no. 4, pp. 20–37, 1987.

[6] M. R. Cutkosky and I. Kao, "Computing and controlling the compliance of a robotic grasp," *IEEE Trans. Robotics Automat.*, vol. 5, no. 2, pp. 151–165, Apr. 1989.

[7] Y. Descotte and J.-C. Latombe, "Making compromises among antagonistic constraints in a planner," *Artificial Intell.*, Dec. 1984.

[8] T. Iberall, "The nature of human prehension: Three dextrous hands in one," in *Proc. 1987 IEEE Int. Conf. on Robotics and Automation* (Raleigh, NC, Mar. 1987), pp. 396–401.

[9] K. Ishii, "Knowledge-based design of complex mechanical systems," Ph.D. dissertation, Stanford University, Stanford, CA, Oct. 1987.

[10] J. Jameson and L. J. Leifer, "Automatic grasping: An optimization approach," *IEEE Trans. Syst., Man, Cybern.*, vol. SMC-17, no. 5, pp. 806–813, Sept. 1987.

[11] Z. Ji, "Dexterous hands: Optimizing grasp by design and planning," Ph.D. dissertation, Stanford University, Stanford, CA, 1987.

[12] J. Kerr and B. Roth, "Analysis of multifingered hands," *Int. J. Robotics Res.*, vol. 4, no. 4, pp. 3–17, 1986.

[13] K. Lakshminarayana, "Mechanics of form closure," ASME Tech. Paper, 78-DET-32.

[14] Z. Li and S. Sastry, "Task oriented optimal grasping by robotic hands," in *Proc. 1987 IEEE Int. Conf. on Robotics and Automation* (Raleigh, NC, Mar. 1987), pp. 389–394.

[15] T. Lozano-Perez, J. L. Jones, E. Mazer, P. O'Donnell, and E. L. Grimson, "Handey: A robot system that recognizes, plans and manipulates," in *Proc. 1987 IEEE Int. Conf. on Robotics and Automation* (Raleigh, NC, Mar. 1987), pp. 843–849.

[16] D. Lyons, "A simple set of grasps for a dextrous hand," COINS Tech. Rep. 85-37, Dep. Comput. Informat. Sci., Univ. of Mass., Amherst, 1985.

[17] M. T. Mason and J. K. Salisbury, *Robot Hands and the Mechanics of Manipulation.* Cambridge, MA: MIT Press, 1985.

[18] M. E. Merchant, "World trends in flexible manufacturing systems," The FMS Magazine, vol. 1, no. 1, pp. 4–5, Oct. 1985.

[19] Y. Nakamura, K. Nagai, and T. Yoshikawa, "Mechanics of coordinate manipulation by multiple robotic mechanisms," in *Proc. 1987 IEEE Int. Conf. on Robotics and Automation* (Raleigh, NC, Mar. 1987), pp. 991–998.

[20] J. Napier, "The prehensile movements of the human hand," *J. Bone Joint Surg.*, vol. 38B, no. 4, pp. 902–913, Nov. 1956.

[21] V.-D. Nguyen, "Achieving stable grasps in 3D," in *Proc. 1987 IEEE Int. Conf. on Robotics and Automation* (Raleigh, NC, Mar. 1987), pp. 240–245.

[22] M. S. Ohwovoriole and B. Roth, "An extension of screw theory," *J. Mech. Des.*, vol. 103, pp. 725–735, 1981.

[23] R. J. Popplestone, "The Edinburgh designer system as a framework for robotics," presented at the 1987 IEEE Int. Conf. on Robotics and Automation, Raleigh, NC, Mar. 1987.

[24] N. D. Ring and D. B. Welbourn, "A self-adaptive gripping device: Its design and performance," *Proc. Inst. Mech. Eng.*, vol. 183, pp. 45–49, 1968–1969.

[25] G. Schlesinger, "Der Mechanische Aufbau der Kunstlichen Glieder," in *Ersatzglieder und Arbeitshilfen*, M. Borchardt *et al.*, Eds. Berlin, Germany: Springer, 1919.

[26] Simrit Corp., *Pneumatically Operating Gripping and Clamping Elements*, Arlington Hts., IL, 1984.

[27] C. L. Taylor and R. J. Schwarz, "The anatomy and mechanics of the human hand," *Artificial Limbs*, vol. 2, pp. 22–35, May, 1955.

[28] R. Tomovic, G. A. Bekey, and W. A. Karplus, "A strategy for grasp synthesis for multifingered robot hands," in *Proc. 1987 IEEE Int. Conf. on Robotics and Automation* (Raleigh, NC, Mar. 1987), pp. 83–89.

[29] G. Westling and R. S. Johansson, "Factors influencing the force control during precision grip," *Exper. Brain Res.*, vol. 53, pp. 277–284, 1984.

[30] A. C. Zimmer, "A model for the interpretation of verbal predictions," in *Developments in Expert Systems*, M. J. Coombs, Ed. New York: Academic Press, 1984, pp. 235–248.

Mark R. Cutkosky, for a photograph and biography, please see page 165 of the April 1989 issue of this TRANSACTIONS.