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# THE DEXTERITY OF MANUFACTURING HANDS

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A selection procedure for manufacturing hands is discussed, based on the two concepts of *i)* a dexterity spectrum and *ii)* a design space framework. Both the dexterity spectrum and the design space framework are discussed in terms of the number of degrees of freedom in a robotic hand/arm system, the resolution, the speed, the workspace, the sensor capability, and the knowledge base. Since the latter features are more qualitative, the evaluation schemes cannot be fully quantitative.

A key idea is that it is possible to position specific manufacturing *hands* and specific manufacturing *tasks* within these evaluation schemes and then make a "design-for-production" decision concerning the most appropriate hand for any given task.

To demonstrate the potential for such a methodology, the attributes of several manufacturing hands are first considered. Some are based on commercially available devices, (e.g. a two-jaw gripper mounted on a force-sensing wrist and Puma 560 arm) whereas others are research-oriented prototypes (e.g. a Utah/MIT 16 degree-of-freedom hand mounted on a Puma 560). The next step in the methodology is to consider the range of tasks that are achievable by each hand. This initially involves discretizing candidate tasks into primitives that can be described with sufficient detail; then, matching these primitives with the capabilities of the hands.

## 1. INTRODUCTION

This paper is motivated by the following idea: there are many industrial tasks worthy of automation; and, there are several robot hand systems available for automating tasks; however, currently, there is no satisfactory scheme that enables a production engineer to evaluate which robot hand system is good for a task that is being automated (and, vice versa, no satisfactory scheme that enables a research engineer to evaluate which tasks can be automated by a robot hand system being developed).

In the paper we define *a manufacturing hand system* to be a conventional 6-degree-of-freedom robot (such as a PUMA 560), plus robot wrist (either passive-compliant or instrumented-compliant), plus an end-effector varying from a simple vacuum cup to a Utah/MIT hand.

During the last 30 years, industrial robot hands have evolved in their manipulation ability from simple pick-and-place machines with a pinch-like gripper (Engleberger, 1980) to better controlled arms with improved grippers backed up by passive or instrumented wrists (Drake, Watson, Simunovicsh, 1977; Cutkosky and Wright, 1986) to anthropomorphic-like dextrous hands (Jacobsen, Wood, Knutti and Biggers, 1984; Salisbury and Craig, 1982; Okada, 1982). A summary of the development of different robot hands is presented in (Pham and Heginbotham, 1986).

The selection of a robotic hand among this range of possibilities involves a compromise. The potential of increased dexterity or flexibility of an anthropomorphic-like hand can only be attained at an expense: dextrous hands, such as the Utah/MIT hand, are more complex, difficult to control and contain many delicate components. These factors combine to make them impractical for current factory use.

A paradigm for discussing this compromise has been presented in terms of a trade-off between dexterity and strength (Wright, 1985). The schematic graph in Figure 1 considers how dexterity and strength change as devices are added to the bare arm. On the left, the heavy-duty bare arm is imagined not to have a force-sensing wrist, but a very simple pinch-like gripper of the kind originally introduced by Engleberger and Devol for their first robot. Such hands are very strong but lack dexterity. In the center of the graph, passive and active wrists may be inserted between the bare arm and the simple two-jaw gripper. Especially with an active wrist, the system is given a similar architecture as a human operating a heavy tool such as a hammer. The fingers grip around the object like a clamp and the fingers do not become an integral part of the manipulation or the sensor feedback. Rather, the sensor feedback and the manipulation is largely concentrated at the wrist. Thus, it has been proposed that many factory tasks are amenable to automation, provided that they fit into this "wrist" category.

On the right side of the graph are finger tasks where light delicate assembly operations and manipulations are required. In the human paradigm, fingers are used for light tasks such as starting a nut on a bolt, adjusting a set screw, writing with a pencil, adjusting a wrist watch, and performing fine, domestic operations. The development of a robotic dextrous hand such as the Utah/MIT hand is therefore targeted at these lighter tasks (Clark et al 1989). While industrial assembly may be unrealistic, prosthetic applications may be an important application area for these hands.

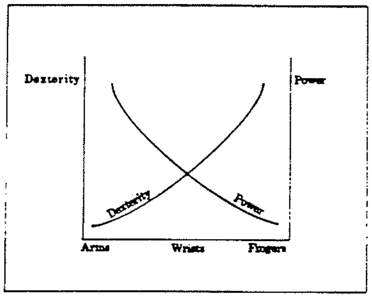

**Figure 1. The trade off between dexterity and strength when an active wrist and then a dextrous hand with active fingers are cumulatively added to a robot arm (Wright, 1985)**

Comparisons with other research in robotic hands must cover a broad spectrum of activities, from theoretical work on the stability of grasps through implementational aspects involving actuators and control methods, and finally to industrial applications and the integration of robot/hand systems with other machinery.

Typical theoretical analyses begin with inquiring about the stability of objects held with three point loading fingers which have compliance or elasticity, normal and tangential to the compact surface (Asada, 1979; Asada and Hanafusa, 1982; Salisbury, 1982; and Cutkosky, 1985). A natural development of the analytical methods concerning the stable, static grasps is an analysis of the closure of a robot hand on an object. Mason, Goldberg and Wang (1989) consider the analyses of the movements of various polygons being closed upon by 2 parallel fingers. Closure involves a pushing and a squeezing phase, the analyses of which lead to a prediction of the object position in the gripper. This analysis is obviously important to robot planning.

The next step beyond the static and quasi-static analyses above is to consider the dynamics and control of grasps achievable by multi-fingered hands. Theoretical work is being done by Sastry (1989). While such work begins with the analysis of grasp type and grasp planning, the main concerns are the derivation of control laws for manipulating objects held by multi-fingered hands. Cole, Houser and Sastry (1989) present analyses for both point-contact fingers with friction and for soft finger contacts. Their work is currently being extended to rolling contacts and sliding contacts. Many novel devices have been developed prompted by such work. For example, a pneumatically actuated robotic hand has been developed to adapt compliantly to a variety of object shapes (Tsach, Chang and Phillips, 1989). The most advanced devices include Salisbury's three-fingered hand (1982), Okada's hand (1982) and the Utah/MIT hand developed by Jacobsen et al (1984) and Hollerbach (1983).

However, for such robot hands to be most useful they must be capable of interacting dynamically with a variety of environments. This is especially important in "high demand" contact tasks, such as grinding or deburring where the hand is to apply a known force, and also reject undesirable high frequency disturbances, while satisfying position constraints. A hand controller must be designed so that the hand will meet such specifications and remain stable when coupled to any environment it can reasonably be expected to encounter. Yet, there are few existing tools for generally controlling hands that can also ensure the stability of such hands when coupled to incompletely characterized environments in carrying out tasks. As a result, one must have some model of the environment to investigate the interactive behavior.

In practice, most real environments are dynamic. Dynamic models assume that the environment exerts forces on the robot hand that are functions of the state of the environment and the hand. The most common dynamic model of the environment is a second-order model (such as a mass-spring-damper system) (Jourdain and Nagurka, 1988). A physically-motivated strategy to analyze the coupled stability of a finger interacting with the environment (or object) has been proposed. The strength of the approach is that it assumes nothing about the environment other than a general impedance model (with an energy-dissipative nature).

In addition to low- and mid-level control strategies, the high-level control problem of trajectory planning must be addressed. Although the problem of trajectory planning for robots has been studied in the literature, especially for determining manipulator paths around obstacles, real time trajectory planning for a multi-fingered robot hand is an unsolved high-level control challenge. To achieve autonomous operation, "scene" information may be available from a pad of tactile sensors and/or a video camera. In general, the scene is very roughly quantized and information is sparse (and at times unavailable). In addition, within a constrained work space, robot fingers must negotiate their paths towards an object, and then coordinate the desired manipulation. A fast "feasible" solution, rather than an "optimal" solution, may often be acceptable. However, a slow "feasible" solution may result in failure (eg., dropping an object).

In summary, this brief review of comparative research shows a wide range of issues in grasping theory, robot hand design and control. In future work, it will be important to develop implementations in which particular hands and their control methods are evaluated for specific tasks. However, we believe it is now equally important to begin to integrate much of the above work into the evaluation frameworks discussed later so that effective cross comparisons can be made and directions for such future research be more clearly established.

## 2. EVALUATING THE POTENTIAL USE OF A PARTICULAR HAND

When robotic hands are developed in laboratories, the efforts of getting them working and carrying out some sample "demos" are the usual preoccupations of the investigators. Potential industrial uses are usually of secondary concern. Moreover, it is rare that the inventors of one particular hand-style compare and contrast their system with others in the community. In the future, if this could be done successfully, then a range of complexity of different hands could be presented to industrial automation engineers involved in automating tasks. In general, no universal schemes yet exist to evaluate the capability and development progress of a particular hand-system, thereby allowing cross-comparisons with other researchers. Some work has been done by the teleoperation community (see [Vertut and Coiffet, chapt. 3.1] for a comprehensive survey) and much can be adapted for robotics work. In particular, the following measures apply:

*Speed:* The single most important factor is the time to perform the task. This is usually measured as a multiple of the time it takes a human to perform the same task. Speed measurements have also been studied by Fitts [1954] who presents specific experiments that we can emulate.

*Accuracy:* In pick-and-place type tasks such as stacking blocks, the accuracy of the alignment of the blocks can be measured. The accuracy with which a predetermined trajectory can be followed (following a curve with a grasped tool) may also be measured.

*Success rate:* Difficult tasks like screwing a nut onto a bolt may not always succeed (without dropping the nut). Thus, the fraction of successful attempts may be measured.

*Training time for the human teleoperator:* In tasks involving teleoperation, performance will improve as the operator practices. The operator's performance as a function of number of attempts or time can be measured and used to measure the quality of the automated parts of the task.

All of these measures will depend on various problem parameters, as well as on one another (speed and accuracy will vary inversely with one another). For example, object size will affect the success of the manipulation. Measuring performance as a function of these parameters will help identify intrinsic limits in manipulability and possibly suggest how workpieces be designed for easy automatic assembly.

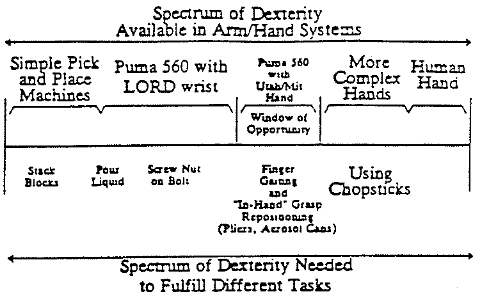

**Figure 2. Dexterity Spectrum**

## 3. THE DEXTERITY SPECTRUM

In the next two sections, the concepts of a "dexterity spectrum" (section 3) and a "design space framework" (section 4) are presented as evaluation procedures for considering the problems discussed before and answering the general question, "Which hand for which task?"

For example, it is clear that the Utah/MIT hand fits onto some *spectrum of possibilities* of robotic hands: the spectrum could include *i)* the very simplest robot arm/hand such as a pneumatic device with an insensate, two-jaw gripper; *ii)* the PUMA 560 merely carrying its standard two-jaw gripper (but with a force sensing wrist) and *iii)* very complex dextrous hands that resemble human hands.

This brings us to a key question - "Where does a device such as the Utah/MIT hand fit on such a spectrum of hand complexity?". And indeed a more important question - "Within its position on such a spectrum, how broad is the set of tasks suitable for a Utah/MIT hand?" In this regard, we coin a phrase: - *window of opportunity*, shown on the top part of Figure 2. We should note that, at present, we have no measure of the index of dexterity shown in the figure and thus the relative positions of these different robot systems along the axis are based on intuition. Clarifying and quantifying these issues is part of our research.

Having proposed a spectrum of complexity of different *robot systems*, the next important questions to ask are - "Given *typical tasks*, where do they most logically fit on this spectrum?" and "Which is the best robot system to achieve the task?" From a pure engineering approach, it can be argued that the task will be most easily implemented by the robot with the simplest engineering. While the Utah/MIT hand can do many of the tasks that the simpler robots can do, it is still important to ask, "How much gain comes from this increased flexibility (and consequent complexity) if a simpler machine can do the task?"

In the lower half of Figure 2, our target tasks for the Utah/MIT hand are listed. With appropriate hard-engineering, a simple robot with a parallel jaw gripper, without much flexibility, can stack blocks and also pick up a container and pour its contents into a second one. However, to screw an arbitrary nut onto a bolt requires more dexterity in the arm system, more repositioning and sensor feedback at the wrist. Thus at this point, it is preferable to use the PUMA with a force sensing wrist. At the extreme, more complex tasks such as finger-gaiting, or operating an aerosol can, or a set of pliers, involves a hand with several fingers, e.g. the Utah/MIT hand. In such tasks, some of the fingers have to be used to stabilize the object or can; other fingers need to be used to rotate the object, or operate the tool, or actuate a nozzle. The complex task of "transitioning in a grasp" is also mentioned in the context of the Utah/MIT hand. This example can be best illustrated by an act of picking up a pen from an arbitrary position on a table and then flipping it around in the hand so that the pen is poised and ready for writing. This in-hand repositioning involves moving from one grasp to another, as shown in the grasp taxonomy tree (Figure 3). The manipulation of most common domestic objects, such as drinking containers, involves such transitions in the hand. We conclude that, generally speaking, when an object needs to be manipulated through large rotations without putting it down, and when tasks involve the operation of multiple fingers in a hand, then in these cases a device like the Utah/MIT hand is needed. Finally, we should re-emphasize that in Figure 2, there are hands beyond the complexity of the Utah/MIT hand that are needed to do more complex operations involving tactile feedback.

Clearly, an important aspect of building general robotic systems is matching the spectra shown in the upper and lower parts of Figure 2. This brings us to the most challenging question for the Utah/MIT hand. How useful is the hand? How broad is the window of opportunity shown for the hand in Figure 2? These questions can be formulated in a negative and a positive hypothesis, shown here.

- **Negative hypothesis:**
  The "window of opportunity" for the Utah/MIT hand is so small and its candidate tasks can be accomplished, in most cases, by a simpler robot: the hand has no practical use.
- **Positive hypothesis:**
  There is a wide range of tasks that cannot be done by simpler robots (such as the PUMA 560 with a two-jaw gripper) creating the need for the Utah/MIT hand: its development therefore opens up many options for prosthetics and manufacturing.

At present, we cannot make categorical statements in favor of one of the hypotheses and, from the literature and discussions with other co-workers, the questions above have not yet been answered. Our case studies and the above "measures of success" are concerned with investigating the negative and positive hypotheses. We anticipate that the "success-criteria" will also lead to an improved measure of "an index of dexterity". As mentioned, the central axis in Figure 2 is at present entirely qualitative. The ideal situation will be to define a quantitative scale on this central axis, running from 0 to 1, and then, be able to quantitatively place robotic systems and tasks on this spectrum. Such a quantitative evaluation will more clearly define the window of opportunity for systems such as the Utah/MIT hand or, for that matter, any other hand system. Establishing the width of this window of opportunity on the axis will reinforce either the negative or the positive hypotheses above. We propose that the dexterity of the Utah/MIT robot hand system relies on the following attributes:

i) the ability to control position and force of a variety of held objects
ii) the ability to change grasps in Figure 3 without dropping the object.

During the course of our research we are attempting to quantify the above. An outline of our methodology is in Figure 4. It contains two "feedback loops", an upper one including the boxes labeled 'Tasks' and 'Task Decomposition', and a lower one including the boxes labeled 'Utah/MIT Hand' and 'Manipulation Primitives'. The experimental plan is to decompose tasks into certain primitive manipulations (the upper loop), where the primitive manipulations have been designed on the basis of the capabilities of our current robotic configuration (the lower loop). We will then attempt to implement and perform the tasks on our robot (boxes labeled 'Build Task' and 'Task Successful?'). Based on the degree of success of this experiment, we may alter both the task decomposition in the upper loop and the available primitives in the lower loop.

Our case study tasks shown in the top left of Figure 4 are:

*Stacking blocks:* Position the hand around each block, grasp it, position the hand near the top of the previously piled stack, release the block, and push it into better alignment if necessary.

*Pouring liquid:* Position the hand near the bottom of the open liquid container, grasp it, position it at an appropriate distance from the target glass, tip it slowly until liquid pours (we assume we know how full the carton is initially), raise the carton upright, position it back on the table, and release it.

*Screwing a nut onto a bolt:* Position the hand around the nut, grasp it, move till it is near the bolt, start the thread, turn as far as possible without losing the grasp, and repeatedly release, regrasp and turn.

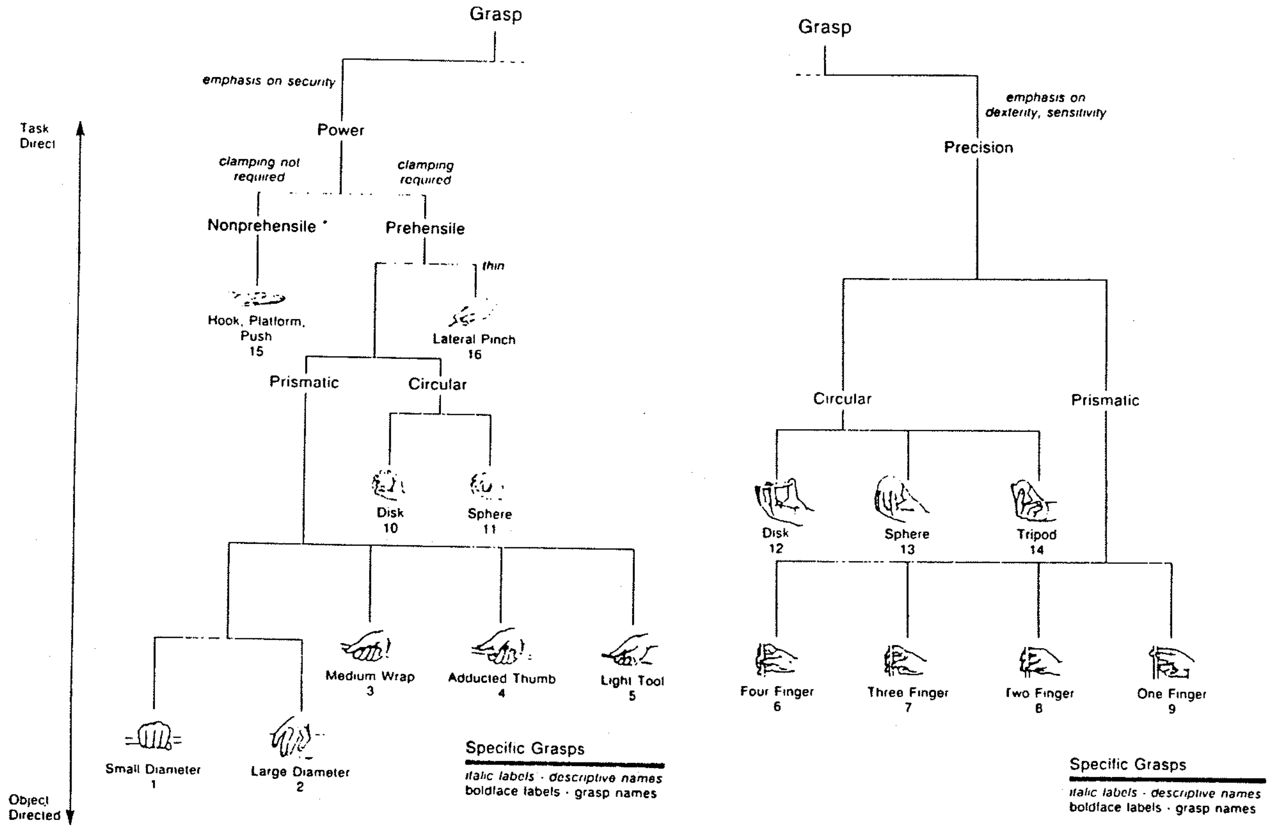

**Figure 3. A taxonomy of human grasps for power and precision grips (Wright and Bourne, 1988)**

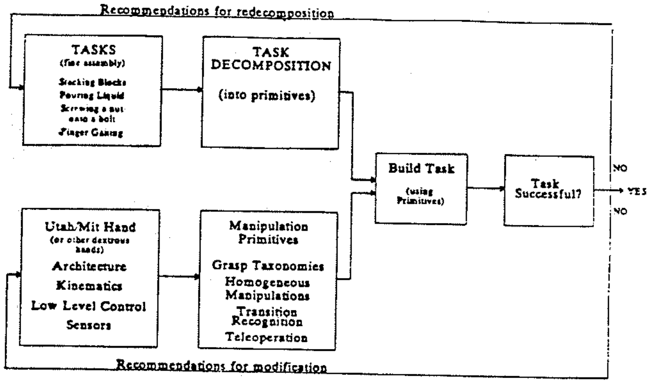

**Figure 4. Research Methodology**

*Finger gaiting:* Grasp an object, and turn it through a large angle by repeatedly turning with three fingers, grasping with the fourth, releasing one of the original three, and turning again.

We thus see that at least the following primitives will be necessary to implement these manipulations:

(1) Free motion of the robot fingers (grasp prepositioning) and Puma. This is needed for all the above tasks. We assume the approximate object shape and position are known. Motion of the Puma will be controlled by teleoperation.

(2) Acquiring a grasp on an object after prepositioning the fingers. Strictly speaking, this is a transition between two primitives: free motion (precontact) of the fingers, recognition of the contact or resistance force, and grasp maintenance (postcontact). The inverse motion, ungrasping, is also required; here one should be careful to release smoothly so as to leave the object stationary.

(3) Turn a grasped object about an axis. This may involve resisting a (smoothly varying) external torque, or simply be free motion. The turning object may or may not be kinematically constrained (e.g. a threaded nut).

(4) Redistribute the grasp forces among the grasping fingers. This is needed for finger gaiting, where one must transition from one grasp to another.

## 4. THE DESIGN SPACE FRAMEWORK

A drawback of the dexterity spectrum ideas in the previous section is that many attributes of robots are "hidden" by the one dimensional line in Figure 2. What makes a system dextrous? Is it the many degrees of mechanical freedom in the Utah/MIT hand? Or the degree to which joint servos can be rapidly updated by the low level controller? Or is it the task level planning in some higher level coordination algorithms? Obviously it is some combination of all of these but with different weightings depending on the task.

The "design space framework" takes the "dexterity spectrum" a step further and we have begun by evaluating different robot systems. We have been compiling classification tables with a wide range of *i)* mechanical design, *ii)* control and *iii)* knowledge oriented aspects of different tasks and robot systems. In order to fill out the above classification tables with sufficient detail and accuracy, some limited experiments are also being conducted with the following manufacturing hands, *all supported* by a PUMA 560 to standardize the basic arm. (Only a few experiments will be needed with the first elementary gripper.)

- a vacuum and/or magnetic gripper with no instrumented wrist
- a basic two-jaw gripper with no instrumented wrist, capable of simple tasks on a CNC machine tool (Greenfeld et al 1989)
- a two-jaw gripper with instrumented wrist, for example see (Cutkosky and Wright 1986)
- a precise finger and palm exhibiting position/force control (Jourdain and Nagurka 1989)
- a Utah/MIT dextrous hand (Clark et al 1989)

Work in progress specifies the attributes of the robot hand-systems and the tasks. In the following three subsections, the attributes of mechanical design, controls and coordination knowledge are described in more detail. In the tables, they are ranked under the 6 hand "clusters" shown. These clusters are our current estimates of appropriate cluster labels. However, those are the subject of ongoing and proposed research and thus the ideas are not completely concretized at the present time.

### 4.1. Mechanical Design Attributes

Mechanical design broadly constitutes the area of kinematics, namely the number of fingers and degrees of freedom and working envelope. It also incorporates the dynamics of the system and is concerned with describing actuator speeds, payloads and accuracy. Figure 5 shows, in tabular form, some of the various mechanical design aspects that we plan to classify according to the hand-system clusters shown along the top of the table. This shows a spectrum of capability from the simplest cluster (i.e. the vacuum cup) proceeding to the most complex cluster (e.g. the Utah/MIT hand and even more advanced hands).

### 4.2. Control Attributes

Figure 6 shows a table of the control features being listed and evaluated. These control attributes are concerned with low level control features such as the maximum speed of response, the bandwidth of the response, and the natural frequency/damping trade off of the system. These have also been listed under the five cluster groups from simple to complex. In fact, most current control methods are dependent upon a complete mathematical representation of the system to be controlled (in this case the robot hand and the environment). This requires that we model the system and describe the system completely (usually using state variable representations). Perhaps it is possible to relax the requirement of a complete system description by employing constraint-based control. In this approach, the task planner (high level) would be given the chore: "get finger 1 to point A, subject to constraints B, C, and D". The low level control would take care of "internal" details (i.e., checking against constraints, dealing with disturbances, detecting and avoiding impending disasters, etc.). The onus is on specifying the constraints properly and completely, rather than the system completely. This area warrants further investigation.

### 4.3. Coordination-Knowledge Attributes

In Figure 7, coordination knowledge is evaluated. In order for low level controls to be orchestrated, there is a need to specify mid and high level task planning operative. Programming at the 'grasp' rather than 'joint' level is an example of mid level coordination knowledge taxonomy, as an example, a three finger grip could close on a pea or a baseball. What is needed here is not a cumbersome joint by joint control program, but a program for 'gesalt' set pre-programmed actions that describe closure on a focal point of the grasp.

At a higher level still, a task planner is needed for accomplishing adaptation to external, unexpected disturbances. Advanced hand systems with sensors will exhibit dynamic re-planning through the use of expert systems or neural networks.

| Hand Types / Mechanical Attributes | Vacuum / Magnetic Gripping | Two jaw gripper (no force sensing wrist) | Two jaw gripper with instrumented RCC wrist | Three degree-of-freedom finger with force & position sensors | Utah/MIT hand with force & position sensors | Human hand |
|---|---|---|---|---|---|---|
| Number of fingers | $a_{11}$(1) | $a_{12}$(2) | $a_{13}$(2) | $a_{14}$(1) | $a_{15}$(4) | $a_{16}$(5) |
| Degrees-of-freedom per finger | $a_{21}$ | $a_{22}$ | $a_{23}$ | $a_{24}$ | $a_{25}$ | $a_{26}$ |
| Total degrees-of-freedom | $a_{31}$ | $a_{32}$ | $a_{33}$ | $a_{34}$ | $a_{35}$ | $a_{36}$ |
| Max finger thickness | $a_{41}$ | $a_{42}$ | $a_{43}$ | $a_{44}$ | $a_{45}$ | $a_{46}$ |
| Max grip opening size of fingers | $a_{51}$ | $a_{52}$ | $a_{53}$ | $a_{54}$ | $a_{55}$ | $a_{56}$ |
| Max effective palm size | $a_{61}$ | $a_{62}$ | $a_{63}$ | $a_{64}$ | $a_{65}$ | $a_{66}$ |
| Resolution of fingertip position | $a_{71}$ | $a_{72}$ | $a_{73}$ | $a_{74}$ | $a_{75}$ | $a_{76}$ |
| Max gripping force | $a_{81}$ | $a_{82}$ | $a_{83}$ | $a_{84}$ | $a_{85}$ | $a_{86}$ |
| Resolution of gripping force | $a_{91}$ | $a_{92}$ | $a_{93}$ | $a_{94}$ | $a_{95}$ | $a_{96}$ |

**Figure 5. Mechanical Attributes of Hand Types**

| Hand Types / Control Attributes | Vacuum / Magnetic Gripping | Two jaw gripper (no force sensing wrist) | Two jaw gripper with instrumented RCC wrist | Three degree-of-freedom finger with force & position sensors | Utah/MIT hand with force & position sensors | Human hand |
|---|---|---|---|---|---|---|
| Number of sensors | $b_{11}$ | $b_{12}$ | $b_{13}$ | $b_{14}$ | $b_{15}$ | $b_{16}$ |
| Resolution of sensors | $b_{21}$ | $b_{22}$ | $b_{23}$ | $b_{24}$ | $b_{25}$ | $b_{26}$ |
| Max speed of response | $b_{31}$ | $b_{32}$ | $b_{33}$ | $b_{34}$ | $b_{35}$ | $b_{36}$ |
| Bandwidth of response | $b_{41}$ | $b_{43}$ | $b_{43}$ | $b_{44}$ | $b_{45}$ | $b_{46}$ |
| Natural frequency | $b_{51}$ | $b_{52}$ | $b_{53}$ | $b_{54}$ | $b_{55}$ | $b_{54}$ |
| Damping ratio | $b_{61}$ | $b_{62}$ | $b_{63}$ | $b_{64}$ | $b_{65}$ | $b_{66}$ |

**Figure 6. Control Attributes of Hand Types**

| | Hand Types / Coordination-Knowledge Attributes | Vacuum / Magnetic Gripping | Two jaw gripper (no force sensing wrist) | Two jaw gripper with instrumented RCC wrist | Three degree-of-freedom finger with force & position sensors | Utah/MIT hand with force & position sensors | Human hand |
|---|---|---|---|---|---|---|---|
| Mid Level | No. of sensors being monitored | $c_{11}$ | $c_{12}$ | $c_{13}$ | $c_{14}$ | $c_{15}$ | $c_{16}$ |
| | Time to process sensor data | $c_{21}$ | $c_{22}$ | $c_{23}$ | $c_{24}$ | $c_{25}$ | $c_{26}$ |
| | Time to determine control action | $c_{31}$ | $c_{32}$ | $c_{33}$ | $c_{34}$ | $c_{35}$ | $c_{36}$ |
| | No. of pre-programmed grip/loading combination | $c_{41}$ | $c_{42}$ | $c_{43}$ | $c_{44}$ | $c_{45}$ | $c_{46}$ |
| High Level | No. of rules in expert system | $c_{51}$ | $c_{52}$ | $c_{53}$ | $c_{54}$ | $c_{55}$ | $c_{56}$ |
| | No. of pre-programmed planning strategies | $c_{61}$ | $c_{62}$ | $c_{63}$ | $c_{64}$ | $c_{65}$ | $c_{66}$ |
| | Time to replan | $c_{71}$ | $c_{72}$ | $c_{73}$ | $c_{74}$ | $c_{75}$ | $c_{76}$ |
| | No. of strategies prior to successful task execution | $c_{81}$ | $c_{82}$ | $c_{83}$ | $c_{84}$ | $c_{85}$ | $c_{86}$ |

**Figure 7. Coordination Knowledge of Hand Types**

Quantifying the mid and high level coordination knowledge is a challenge. The mid level coordination capability hand systems can be evaluated, to some extent, by the number of pre-programmed grips in their library of actions. The high level coordination capability can be evaluated by the number and range of sensors and then by the number of reactive rules in a modulating expert system.

### 4.4. Task Decomposition Clusters

Figure 8 shows task clusters that have increasing complexity. Along the top of the table, the clusters vary from simple peg-in-hole operations where the alignment of two objects is the important feature, to complex tasks such as finger gaiting in fine manipulation where coordinated finger control is necessary leading to stable grasping and object rotation. Figure 8 shows task clusters versus mechanical attributes. Two other tables (not shown) would show clusters versus control and coordination knowledge attributes as in Figures 6 and 7.

In designing hands for carrying out tasks in the manufacturing environment, there is a need for devising a scheme for representing the actions to be performed. This is distinct from the grasp taxonomy of Figure 3 in several ways. First, the grasp taxonomy is heavily anthropocentric. If we use the grasp taxonomy alone to design a manufacturing hand, we can expect to see a clear tilt towards a dextrous hand modeled on the human hand (e.g., the Utah/MIT hand). The task taxonomy should not necessary contain this bias. Second, a grasp is a precursor to motion, and is useful to the extent that it provides clues about the manipulation task. The development of an action representation, allows us to go directly to the manipulation needed. Thus, this part of the ongoing work is addressing a scheme in which actions (in contrast to the ways of performing them) can be represented. The scheme will attempt to be general (to avoid anthropocentrism from creeping in) and complete (to the extent that many, if not most, manufacturing tasks can be carried out with the developed set of action primitives). As an example, the action taxonomy will offer a representation of a given task (such as fixturing a workpiece). This representation may be in terms of a range of trajectories, perhaps specified in terms of "lower" and "upper" bounds. The idea is that a given trajectory might be optimal for given a hand design, but not necessarily for all hands. Thus, prior to matching to a particular hand, the task is represented in terms of "desirable" actions or ranges of acceptable actions that will enable the task to be carried out. Once the task is specified in terms of these action primitives, the link to task planning for the purpose of control should be straightforward. This will help simplify the control requirements. Overall, an approach that ignores or disables unneeded abilities for a particular task might be quite useful. This concept extends beyond ignoring certain sensor readings when they are not of interest. It is certainly possible, for example, to lock certain joints of a hand for a particular task, hence saving control effort for that task and simplifying the control problem (ie., freeing computational resources for perhaps more important control tasks).

As a final note on task decomposition, it may be helpful to view task specifications as task-based constraints. (Note that there are additional "native" constraints, including mechanical constraints, such as limits on joint angles and limits on torques, that also must be met. If these task-based and "native" constraints are in conflict, the task cannot be accomplished.) In this perspective, the action primitives of a task would correspond to (in)equality constraints of some dynamic variables (eg., state and control variables). This also may offer a natural connection in solving the problem.

### 5. DISCUSSION

An everyday analogy is briefly presented. The classification of robot arm + wrist + hand systems into different attributes is similar to the *Consumer Reports* and *Road and Track* evaluations of automobiles. Here, categories, performance indeces, costs and qualitative data on comfort are tabulated. We note that such comparisons are usually done within "clusters". Rather than compare all vehicles across the board, they are grouped into labelled clusters such as off road vehicles or four door family cars or luxury sedans.

At the same time, the classification of tasks into different attributes is similar to the work done by a 'market research' division of an automobile company in seeking out different types of consumer clusters for its products. If both types of classification are done well, good information is presented to a potential customer preparing to purchase a vehicle. He/She will fit personal or family needs into one of the market research clusters; identify the appropriate coarse cluster in the automobile domain; and then make finer choices within the cluster.

Thus in our work we wish to provide an evaluation scheme that will make the manufacturing engineer as informed as the above consumer. He/She needs to be able to classify the industrial task, allocate it to its cluster, identify the appropriate robot system cluster and then fine tune to select the final device (Figure 9).

Identifying and labelling the clusters on both sides of Figure 9 and, secondly, getting the appropriate mapping between them are probably the most challenging aspects of such work. These are the main subject of the ongoing research.

| 6 of n Possible Task Types / Attributes | Pick-and-place | Peg-in-hole | Compliant peg-in-hole | Contour finding and following | Fine manipulation (eg. screwing nut onto bolt) | Fine manipulation with finger gaiting |
|---|---|---|---|---|---|---|
| Number of fingers | $d_{11}$ | $d_{12}$ | $d_{13}$ | $d_{14}$ | $d_{15}$ | $d_{16}$ |
| Degrees-of-freedom per finger | $d_{21}$ | $d_{22}$ | $d_{23}$ | $d_{24}$ | $d_{25}$ | $d_{26}$ |
| Total degrees-of-freedom | $d_{31}$ | $d_{32}$ | $d_{33}$ | $d_{34}$ | $d_{35}$ | $d_{36}$ |
| Max finger thickness | $d_{41}$ | $d_{42}$ | $d_{43}$ | $d_{44}$ | $d_{45}$ | $d_{46}$ |
| Max grip opening size of fingers | $d_{51}$ | $d_{52}$ | $d_{53}$ | $d_{54}$ | $d_{55}$ | $d_{56}$ |
| Max effective palm size | $d_{61}$ | $d_{62}$ | $d_{63}$ | $d_{64}$ | $d_{65}$ | $d_{66}$ |
| Resolution of fingertip position | $d_{71}$ | $d_{72}$ | $d_{73}$ | $d_{74}$ | $d_{75}$ | $d_{76}$ |
| Max gripping force | $d_{81}$ | $d_{82}$ | $d_{83}$ | $d_{84}$ | $d_{85}$ | $d_{86}$ |
| Resolution of gripping force | $d_{91}$ | $d_{92}$ | $d_{93}$ | $d_{94}$ | $d_{95}$ | $d_{96}$ |

**Figure 8. Mechanical Attributes of Tasks**

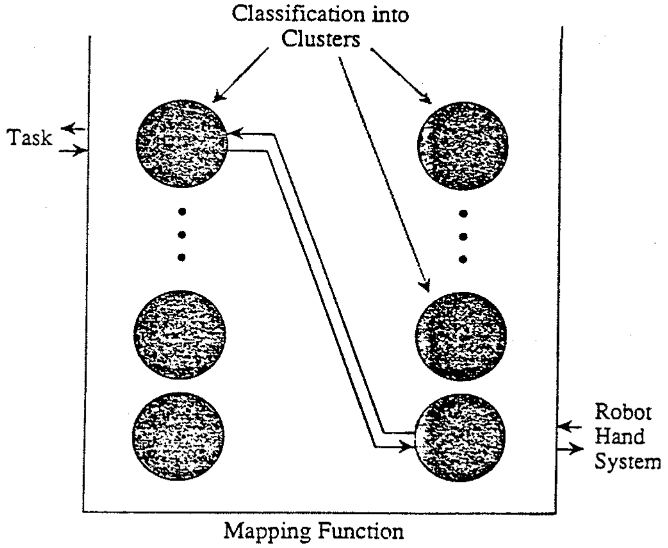

**Figure 9. Correlating Hands and Tasks**

## 6. CONCLUSION

The basic theme of this paper is that, as demonstrated by our previous efforts and efforts of the robotics research community, we can build hands and robots with significant potential abilities, but we have difficulty in realizing that potential. Part of this difficulty is due to a fundamental lack in our ability to control the complex mechanisms we can construct. Part of this difficulty is due to our inability to appropriately match hands to tasks. We are challenged in our understanding (ie., decomposing) real-world tasks into "bite-size" subtasks that can be carried out through fundamental control actions. Evidence for the difficulty in achieving the potential of available robotic hands is the fact that truly autonomous operation of these devices is not yet possible. By studying the mechanical design attributes, control system design attributes, coordination knowledge attributes and the sequence of primitive actions of the task to be performed, we assert that a streamlined design approach for matching hands to tasks can be carried out and the usefulness of hands will be increased.

## 7. ACKNOWLEDGEMENT

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