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# Issues in Human/Computer Control of Dexterous Remote Hands

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## Abstract

Much research on dexterous robot hands has been aimed at the design and control problems associated with their autonomous operation, while relatively little research has addressed the problem of direct human control. It is likely that these two modes can be combined in a complementary manner yielding more capability than either alone could provide. While many of the issues in mixed computer/human control of dexterous hands parallel those found in supervisory control of traditional remote manipulators, the unique geometry and capabilities of dexterous hands pose many new problems. Among these are the control of redundant degrees of freedom, grasp stabilization and specification of non-anthropomorphic behavior. ~~This paper will give~~ an overview of progress made at the MIT AI Laboratory in control of the Salisbury 3 finger hand, including experiments in grasp planning and manipulation via controlled slip. We also suggest how we might introduce human control into the process at a variety of functional levels. is give

## Introduction

Robot hands have the potential to increase the utility of teleoperator or *telerobotic* systems systems by a large amount. By robot hands we refer to the emerging generation of complex, articulated mechanical hands designed for computer and/or human control. While such complex devices have yet to see application outside of research environments, significant progress has been made in the development of manipulation models, hand control and mechanics [Mason and Salisbury][Jacobsen]. Such capacities as secure grasping, controlled grasp force and impedance, controlled slip, cartesian control of fingertip and object motions and a lisp-based language for hand control have been demonstrated [Salisbury, Brock and Chiu].

Autonomous, program controlled hand systems represent one extreme of the range of command modes in which we expect the hands in telerobotic systems to operate. The other extreme is typified by the purely mechanical remote hands built by [Jameson 87] and proposed by [ADL]. These devices utilize mechanical linkages to conduct forces and motions imposed on the master links to the output hand. Ultimately we envision systems which will take advantage of both direct and preprogrammed control of hands, permitting both human intervention in programmed tasks and computer augmentation of manually controlled operation. The motivation for using such complex end effectors lies in improvement of manipulative dexterity and adaptability that we expect to achieve. In order to assess this potential against the costs of increased complexity it is important that one understand the unique functional capabilities offered by complex articulated hand.

## Hand Functions

The functions which hands are required to perform can be divided into several areas. Prehensile, manipulative and sensory functions are perhaps the most common. In human experience they often occur in combination with each other in a mixture of exploratory and purposeful motions. In performing complex tasks humans simultaneously employ all three functions to verify, guide and plan the sequence of operations performed. In the robotic world we are not yet so lucky as to be able to smoothly integrate these complex functions into a synergy of action; current robotic systems employ a rather loose coupling of their prehensile, manipulative and sensory functions, both structurally and operationally.

Prehensile capability implies the capacity to hold object in some controlled state relative to the hand. This requires that the grasp allow exertion of sufficient restoring forces on an object to hold it against arbitrary disturbance forces. Secure grasping requires at least that there be sufficient dimension to the collective effect of forces acting through all the contact points to span the space of disturbance forces which may act on the object. For spatial motion of rigid objects this is six. The constraints imposed by contacts can be divided into structural constraint and frictional constraint. A grasp which employs more structural constraints will be more secure against large disturbance forces; frictional constraints will cease to be active if disturbance forces become too large in certain directions. The dimension of the net forces acting on the grasped object can be no greater than six, therefore if extra freedoms in force exertion exist, (i.e. more active joints) then the hand has the freedom to adjust the internal forces. These internal forces may be varied without changing the net force acting on the body. They do permit, within certain limits, changing the direction and magnitude of forces acting through individual contact points. This freedom in allocation of grasp forces permits some degree of optimization of the grasp. One potential criterion is minimizing the reliance of a grasp on friction constraints. See also [Cutkosky], [Kerr] and [Jameson].

Manipulation of objects with a hand can take several forms. It may simply hold an object securely relative to the wrist and rely on the rest of the arm for imparting motion. This is typical of most robots and of humans moving relatively large objects. Motion of smaller objects can be achieved with the fingers alone. Objects held in the fingertips can be moved and rotated short distances without breaking or sliding finger contact. Larger motions within the hand require controlled slipping and repositioning of fingers. In manipulating very large objects the hand may recursively act as a large fingertip in concert with other cooperating hands.

Sensing includes a number of functions ranging from simple measurement of the mechanism's position, velocity, acceleration and force states, detection the characteristics of contacts with objects such as location and force distribution to the measurement of manipulated object characteristics such as curvature, texture and temperature.

## Dexterity

Dexterity then, is the integration of all these and more capacities into a higher level of competence. It is a quality of manipulative capability which implies a degree of skill and deftness of operation. These in turn, depend on the quality of motion, sensing and control. If we look at examples of increasingly dexterous motions the distinction between prehension, manipulation and sensing begins to blur. Sensing the shape of an object may require manipulation of it to detect its contours. Holding an object may require adjusting to a more favorable grasp. And, moving an object may require a sequence of regrasping. Humans easily integrate these functions to perform wonderfully complex operations. A high degree of mechanical functionality, rich sensory input and intellectual capacity combine to produce human dexterity. Dexterity in the machine sense is still in its infancy and suffers from limited functionality in all three areas.

*Machine dexterity* necessitates that a high degree of mechanical functionality be available, independent of whether the commands originate with a human or a computer. In a telerobotic system the hands and arms will be controlled by combinations of human and computer command, but the net dexterity can be no greater than the mechanical and sensory capability of the system. These elements of machine dexterity can be divided into several broad categories.

Kinematics. There must be sufficient contacting surfaces to impart the required degree of constraint to manipulated objects. There must be sufficient degree of freedom of motion in the hand and fingers to impart required motions and forces to objects. The joint ranges of motion and link proportions must be sufficient to achieve required grasps and motions.

Dynamics. The mechanism must be fast enough and strong enough to do the required work. It must have sufficient resolution of motion and force exertion to perform the required tasks.

Sensing. The type, accuracy, sensitivity and resolution of sensing must be adequate to provide required perception of hand states and object interactions.

The kinematics and dynamics of a hand limit the controllability of states of the manipulated objects. The sensory system limits the observability of task states. A mechanism lacking certain degrees of freedom my not be able to effect certain motions of a manipulated object; a mechanism lacking certain state information may not be able to detect particular motions. Thus the controllable and observable states permitted by a hand must overlap in the dimensions in which we want to achieve closed loop control. Beyond these requirements, a dexterous hand must be constructible, reliable and efficient - a tall order for mortal designers.

The shortcomings in current robot dexterity can be alleviated to some degree by human intervention. Structurally, improvements can be made by redesign of the mechanism to include required freedoms of motion and "active" surfaces. By active surface we mean surfaces on the hand (arm, body or whatever) that may be brought into play to contact and impart motion to manipulated objects. Functionally, such capabilities as force control, stiffness control, programmed reflexes, and programmed micro-tasks may be added. Improvement in mechanisms and servos will improve the quality of these functions. Intellectually, commands may be augmented by writing better and more "intelligent" programs, and/or a human may assume more direct control via analog input devices, ranging from switches to complex master devices. Perhaps the most difficult aspects of machine dexterity are the closely coupled intellectual and perceptual components. In performing truly complex tasks which require a high degree dexterity the demands for high level "understanding"of task goals and progress is greatest. While increasingly more autonomous systems will be developed, it is at this high level that direct human intervention is of immediate value.

## Human Intervention

The human may intervene in the telerobotic manipulation process in a number of ways. At the programming level this will be limited by our ability construct systems able to model tasks physics, automatically plan operations and react to unexpected situations. At the direct interaction level the human will be coupled though a master control device to the hand and arm control system. Such master devices are designed to measure motions and forces imparted by the human on the device which are in turn used to generate commands for the remote hand.

The motions the operator will be able to perform and the information he will be able to acquire will depend upon the mechanical and sensing qualities of the master device. In fact, the qualities required of the master mirror those of the remote hand. The human can directly control no more degrees of freedom of motion than present in the master device and may directly sense no more force or kinesthetic information than can be reflected to the master. Such direct control implies that the master must be a *kinematic replica* of the remote hand with a one-to-one correspondence between master and remote joints. Control of this type has been demonstrated with the Utah/MIT hand [Jacobsen] in a non-force reflecting mode. Even without the benefit of force reflection to the master reasonable dexterity can be achieved through visual feedback and the operator's ability to anticipate required motions without feedback. The challenge of designing a force reflecting kinematic replica master hand of sufficient quality to be useful is a formidable one and suggests that we also consider reduced complexity master devices.

A *generalized master* for controlling finger motions might consist of thimble-like receptacles into which the operator's fingers are placed. These would be supported by a linkage capable of following the finger motions and exerting forces upon them. This mode of control would not necessarily preserve the one-to-one correspondence between human and robot joint motions; it would require computer mediation to resolve these motions. It is perhaps most appropriate for very dexterous manipulation of objects held in the finger tips where we may abstractly view the robot fingers as a collection of force applicators.

An even simpler master might be constructed in the form of a flexible handle. This *deformable master* could consist of a handle with one or more articulated surfaces that the operator presses against during operation. It would be limited to reflecting the net force acting on the grasped object and perhaps one or two of the internal grasping forces. Movement of the robot fingers would depend more heavily upon prespecified and computer controlled coordination patterns.

As we move from complex to reduced freedom master devices we must map commands from the master into the more complex motions of the robot hand. This may be done by assigning master motions to vectors of robot joint motions. Sensory information from the remote hand would have to be mapped back to the master. The choice of these mappings would depend upon what variables are most appropriate for human intervention and what variables may be assigned to computer control. In all cases the control of the hand would have to be integrated with the arm control. Any master for commanding finger motions would probably best be connected to the master device used for commanding arm motions.

This would tend to preserve the operator's kinesthetic sense and help promote synergistic use of the hand and arm as a whole.

As experience and capability with autonomous hands accrues, the functional capabilities developed will be able to assist the human operator to greater degrees. In the following section we describe some of our progress in autonomous robot hand control as a means of suggesting elements which ultimately may be integrated into a telerobotic system.

## Experimental Hand Environment

As part of our group's research in dexterous hand manipulation with the Stanford/JPL 3-Finger Hand (Salisbury Hand) we have developed the experimental environment described in [Salisbury, Brock and Chiu]. This hand, shown in Figure 1, has three fingers each with three active joints for a total of 9 degrees-of-freedom. It has been designed to have the minimum number of freedoms required for securely grasping and arbitrarily moving objects held in the fingertips as described in [Mason and Salisbury]. The control system employs the hierarchy of computers shown in Figure 2. There are 12 microprocessors at the lowest level for individual motor control. A VAX 11/750 is used at the mid-level for controlling finger trajectories and various monitoring functions. Figure 3 depicts the data structure used to describe actions at the joint level. It is essentially a linked list of joint space trajectory polynomials, with associated stiffnesses and condition monitors. Simple and rapid reacting to triggered conditions may occur at this level, including sending a message to the Lisp machine. A Symbolics 3600 Lisp machine is used for commanding cartesian motions of the hand, to react to triggered conditions and to provide a flexible user interface for new modules. Primitive capabilities for the system include position, force and stiffness control. The system permits commands and sensory information to be specified in joint, fingertip and grasped object coordinate systems. For reasons of efficiency and modularity the VAX trajectory and force control systems operate entirely in joint space. Cartesian and more abstract frames of reference are reached through the Lisp interface.

The system has become a test bed for verification and development of higher level functions required for dexterous, autonomous operation. Among the capabilities that have been demonstrated are a contact resolving sensor, a grasp planner module and a controlled slip module. The contact resolving sensor developed by [Brock 84] and [Salisbury 84], shown in Figure 4, permits locating the position and orientation of a contact and well as the determination of the tangential (frictional) and normal (structural) components of the contact force. It has been used to map the contours of an object placed in front of the hand. The grasp planner developed by [Nguyen] has been used to determine and execute stable force-closure grasps on a 10cm cube. The planner determines acceptable grasping surfaces and specifies appropriate finger tip stiffness for polyhedral objects. Because the planner uses only the physics of grasping to guide it and because the hand has a range of motion beyond anthropomorphic, the planner identifies a number of unusual (to humans) secure grasps. These would be uncomfortable for a human to use but are perfectly acceptable for the robot. [Brock 87] has developed a module which permits executing motions using controlled slip within the hand. His analysis shows that by modulating the internal forces in an grasp, the grasp constraint (or freedom) may be altered in a predictable way. By partially relaxing the grasp and then by imposing forces with other fingers, objects or gravity, a grasped object can be made to move under controlled slip conditions. Repeated 180 degree rotations of a grasped block using gravity have been demonstrated as well as the use of one finger to rotate an object held between the other two fingers.

The stiffness control system was originally designed to impart controlled stiffness to grasped objects as might be required to place a peg in a hole or push an object into alignment. We have found that it also permits construction of stiffness that aid in the acquisition of objects. One particularly useful and simple construct we have employed to construct joint space stiffness matrices makes use of the fact that a matrix of rank $n$ may be spectrally decomposed into a weighted sum of $n$ unitary matrices. For example, if $K$ is a matrix of rank 9 with nine linearly independent unit eigenvectors, $k_i$, and eigenvalues, $\lambda_i$, then

$$K = \sum k_i * k_i^T * \lambda_i$$

If $K$ is our joint space stiffness matrix then the elements of $K$ represent the rate at which the torque increases on the $i$th joint for a given deflection in the $j$th joint. The principal stiffness "directions"are defined by each $k_i$. In this case the direction may be simply the motion of a particular joint ($k_i$ has one non-zero element) or it may be a combination of joint motions. By choosing directions along which we wish to resist motion, $k_i$, and magnitudes of stiffness along those directions, $\lambda_i$, we can construct $K$ from the above relationship. If a set of directions is chosen which do not span the full space of motion, there will not be resistance to motion in the unspanned direction.

It is also possible to use the reverse of this process to remove certain stiffnesses from a grasp. For example to permit the two fingers to balance the forces on them against the thumb, we would want to remove stiffness for differential motion of the fingers (here we mean moving finger 1 up while finger 2 moves down). By taking a nominal joint space stiffness, $K$, of full rank (for example, a diagonal matrix) and subtracting the matrix $Kx_1x_1^T$ from it we reduce the rank of $K$ by one. (This is strictly true only if $x_1$ is an eignevector of $K$, but often close enough.) If $x_1$ is a vector representing the desired differential motion of the fingers then the reduction of $K$'s rank corresponds to the freedom introduced between finger 1 and 2. In general we can construct a new reduced rank stiffness matrix by removing the stiffnesses from the "directions" in which we require compliance:

$$K_{\text{new}} = K - Kx_1x_1^T - Kx_2x_2^T - \cdots$$

Current experimentation is concerned with integrating Brock's slip analysis with a controlled slip planning module. In the near future the hand will be mounted on an arm for use in developing coordinated hand and arm operation. It appears that with a contact resolving fingertip sensor on each finger we will be able to implement an online grasp force controller which will seek to maximize structural restraint in the grasp. The same sensor will be used to detect incipient slip conditions by constant monitoring of normal and tangential force ratios. While all the above capabilities were designed for autonomous operation, it is clear that they can easily be integrated with some real time human intervention. It is easy to imagine master generated trajectories superimposed upon controlled grasp stiffness and condition monitoring. Significantly more difficult will be the problem of reflecting the force and kinesthetic information of grasping and inter-digit manipulation.

## Conclusions

We have attempted to give a brief view of some of the mechanical and control characteristics upon which increased telerobotic capacity depends. It is clear that the successful cooperation of human and machine capabilities in hand control will depend both upon advancements in autonomous robot control and in the mechanics of the human/machine interface. The degree of complexity of such systems which will be both useful and tolerable may be ultimately best determined as we gain more experience with their use.

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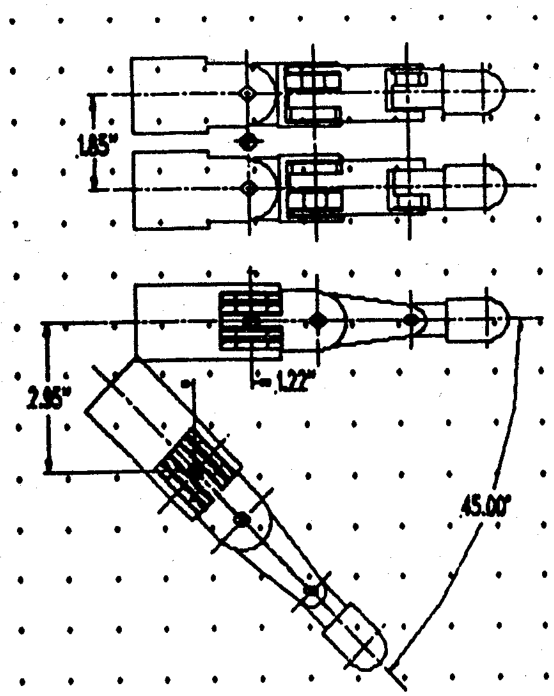


Figure 1. Stanford/JPL Hand, top and side view.

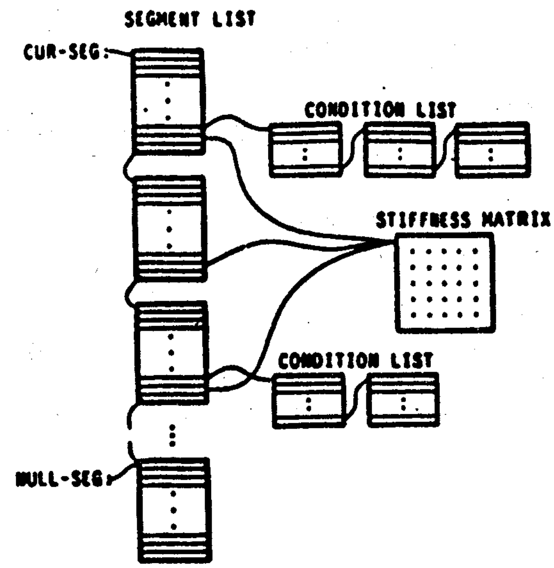


Figure 3. Motion Descriptor Data Structure.

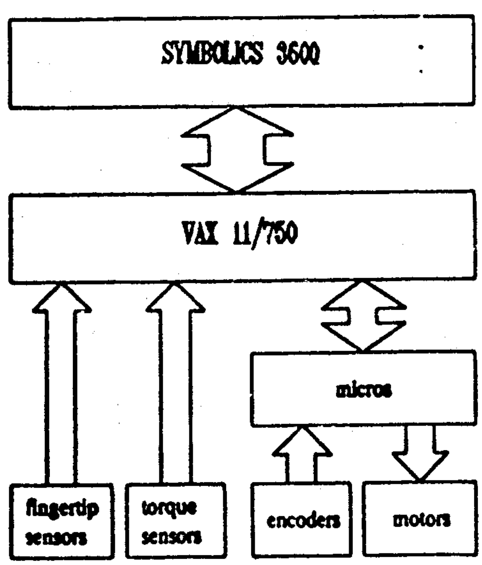


Figure 2. System Architecture.

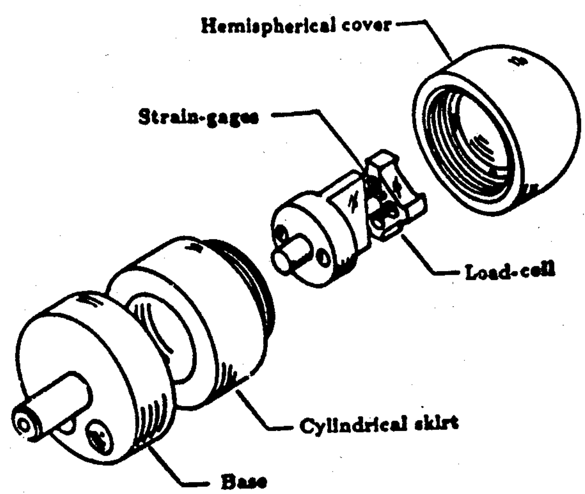


Figure 4. Force Sensing Finger.