A Survey of Dextrous Manipulation

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Abstract

The development of mechanical end effectors capable of dextrous manipulation is a rapidly growing and quite successful field of research. It has in some sense put the focus on control issues, in particular, how to control these remarkably humanlike manipulators to perform the deft movement that we take for granted in the human hand. The kinematic and control issues surrounding manipulation research are clouded by more basic concerns such as: what is the goal of a manipulation system, is the anthropomorphic or functional design methodology appropriate, and to what degree does the control of the manipulator depend on other sensory systems. This paper examines the potential of creating a general purpose, anthropomorphically motivated, dextrous manipulation system. The discussion will focus on features of the human hand that permit its general usefulness as a manipulator. A survey of machinery designed to emulate these capabilities is presented. Finally, the tasks of grasping and manipulation are examined from the control standpoint to suggest a control paradigm which is descriptive, yet flexible and computationally efficient[1].

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1. The Human Hand

In developing the dextrous manipulator, it is common to model the attributes of the human hand which make it such a versatile end effector. The practicality of such an approach has been the topic of considerable discussion. While the human hand is capable of performing quite intricate tasks , it is also limited in its ability to transfer power. In any event, the human hand provides an existence proof of an extremely versatile manipulator with which nearly every investigator is familiar. For these reasons, this survey of grasping technology begins with a review of the physiology of the human hand and grasping primitives which this physiology supports.

1.1. Kinematics

The kinematic character of the human hand is discussed by Lian *et al.* [44]. The index finger of the human hand consists of three joints, the proximal joint is called the metacarpal-phalangeal joint and has two degrees of freedom. It is capable of adduction-abduction over a range of approximately 30 degrees, as well as flexion-extension of approximately 120 degrees. The next two joints of the human finger are the interphalangeal joints. These are hinge joints with only one degree of freedom and a range of motion of approximately 90 degrees.

The thumb is a more complex mechanism, but for the sake of this discussion we will simplify it somewhat by offering the following description. The proximal joint is called the carpometacarpal joint and contains 2 degrees of freedom (2 DOF). The first DOF is adduction-abduction with a range of motion of approximately 90 degrees. The axis of this rotation is skewed somewhat from the plane defined by the fingers and is not entirely understood. The second degree of freedom operates the joint in flexion-extension with a range of motion of slightly less than 90 degrees. This motion is entirely within the plane defined by the palm. The next joint of the thumb is the metacarpal-phalangeal joint whose predominate DOF is that of flexion-extension from the plane of the palm towards the palm over a range of about 60 degrees. The last (distal) joint of the thumb is the interphalangeal joint. This joint is a simple hinge joint with one degree of freedom which allows a range of motion of about 90 degrees.

The grasps which these structures support have been described in texts on biomechanics [39], as well as observed in detail during the execution of representative manufacturing grasps [9]. The enumerated instances are typically distinguished by noting the relative amount of dextrous manipulation and power transmission. The human hand accommodates these somewhat independent modes of operation by involving strong forearm muscles in a grasp when power must be transmitted to the environment. The result is a wrap-around grip that maximizes contact surface area by involving the palm as well as the fingers [68]. This configuration also tends to square[2] the wrist to the detriment of dexterity.

1.2. Biological Sensors

The mechanics of human motor and tactile sensing is quite well understood. The specialized structures which transduce both internal and external signals, and the pathways of control are well documented [8, 18]. However, the information content of the resulting composite signal and the amount of processing done *en route* to the brain is not well understood. The purpose of this section is to expose some of these issues in an effort to develop a perspective on the complexity, redundancy and distributed

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[2] the action of strong finger muscles in the forearm tend to drive the wrist towards its neutral position

nature of the control of the human hand. The following discussion describes some of the structures involved in contact and thermal sensing. These structures are presented in Figure 1-1.

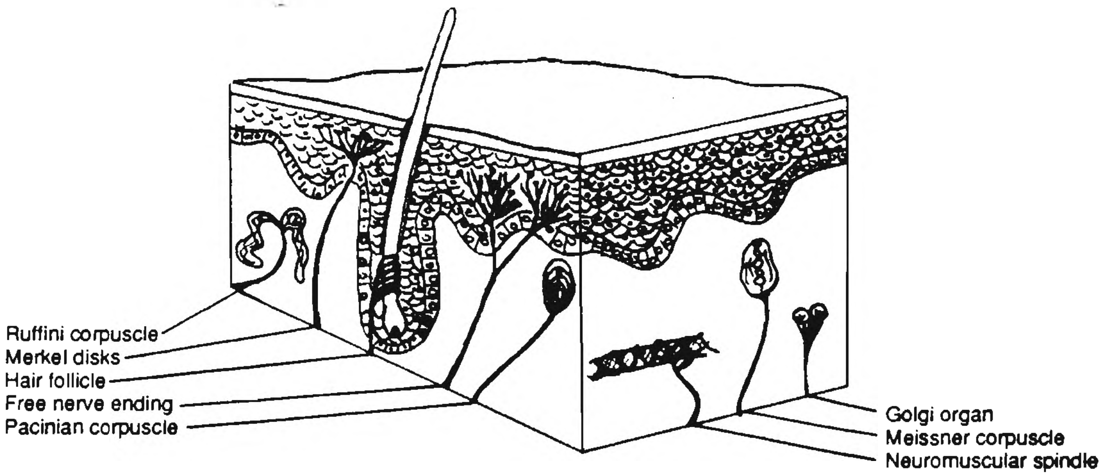


Figure 1-1: Some of the Sensors in the Skin of the Hand

Internal Receptors: Motor control in man involves control of antagonistic muscle groups which allows the stiffness of each joint to be modulated. The control of these muscle groups involves the acquisition of sensory data which describes both position and forces. Internal receptors contribute to the sensing of the relative position of the parts of the body, a "sense" termed proprioception. Four receptors of this type are described below [8, 42].

- Neuromuscular spindles sense the degree of stretch in the muscle fiber. These receptors are in some degree responsible for the reflexive cohesion of the skeleton as well as providing precise movement control. They come in two "flavors"; one that responds to high frequencies and another that responds to low frequencies and DC traction.

The response bandwidth of any particular receptor is a function of the type of nerve terminations. Primary terminations respond to high frequencies while secondary terminations measure low frequencies and continuous traction.

- The Golgi organ exhibits a very slow response and contributes to the control of muscular tension by measuring the degree of stretch of the muscle fiber at the tendon-muscle interface.
- The articular surfaces in the joints of the body produce signals proportional to extreme position, velocity, or ligament tension. These receptors are not analogous to continuous potentiometers, but provide feedback for extreme movement of the joint.
- Ruffini corpuscles represent the final category of internal receptor. This sensor functions as a thermal receptor and may contribute to the sense of kinematic forces and movement (accelerations).

Epidermal Receptors: These receptors are distinguished from those above in that they respond to external stimuli. Perhaps the most intimate interaction of the human nervous system with its external environment is that of the hair. Hair cells have a variety of functions, for example, they perform as proximity sensors, reporting such things as the inertia of the atmospheric fluid that we live in. The contribution of the hair cells to the recognition of the environment is, however, limited and will not be considered further here.

Epidermal receptors provide the most direct indication of a general mechanical couple between the skin surface and an external object. The sensors in the epidermis are characterized by two types of receptors.

- Merkel disks are sensory receptors with a large bandwidth which can respond to both compression and shear stimuli.
- Free Ended Nerve Fibers consist simply of nerve fibers with free endings which respond to a variety of stimuli including temperature and pain. These receptors are classified by their diameter, conduction speed, sensitivity or threshold level, and the presence or absence of a myelin sheath. The performance of these sensors is proportional to the diameter of the nerve fiber. As the diameter increases, the threshold stimulation decreases, the amplitude of output signal increases, the duration of each signal impulse increases, and the velocity of the signal increases. The presence of a myelin sheath induces a somewhat different conduction path in the nerve fiber which increases the velocity of propagation. The types prevalent in the epidermis are the so called A, and C type free ended receptors. Type A has a relatively large diameter and is myelinated while type C is smaller, more numerous and unmyelinated.

The signal output of any one of these epidermal neural receptors consists of a generated potential, which is proportional to the stimulus level. When the generated potential exceeds a threshold value, an action potential is induced. This potential impulse is a constant amplitude spike whose frequency is proportional to the level of stimulation. When the threshold value of the receptor is exceeded the input stimulation is encoded in the frequency domain. The threshold varies from receptor to receptor so that increased stimulation corresponds to more numerous signal responses.

Dermal Receptors: The dermis is represented by two types of receptors [8]

- Meissner corpuscles respond to light touch; they are located beneath the convoluted dermal papillary layer. These structures are ovoid with the major axis perpendicular to the skin surface and contain neural fibers running in vertical and horizontal directions. The Meissner corpuscles are specialized high frequency transducers.
- Pacinian corpuscles (as distinguished from the intramuscular pacinian type receptors) respond best to accelerating mechanical displacement rather than constant velocity deformation. These sensors are quite sensitive to pressure but are not sensitive to direction, suiting them to the transduction of vibration stimuli.

1.3. Biological Performance Specifications

To this point, the properties of the various sensory receptors have been described only in relative terms. It is instructive to discuss the range of absolute values that these parameters may reach. Table 1-1 presents a guide which is useful in this regard.

When considering the diversity, specialization and redundancy of the sensory information provided by the skin and muscle, it is apparent that the implementation of an active, touch feedback, dextrous manipulator in humans requires a complex integration of "bio-ware." An indication of the complexity of "touch" in humans is the fraction of the somatosensory cortex that is devoted to it. Figure 1-2 is a graphical depiction of just this. Note the amount of cortex dedicated to the hands and feet [27]. The

frequency response	0 to 400 Hz (+ very high freq)
response range*	0 to 100 grams/mm^2
sensitivity*	approx. 0.2 gms/mm^2
spatial resolution*	1.8 mm (about 1.35/mm^2)
signal propagation	motor neurons 100 m/sec sensory neurons 2 to 80 m/sec autonomic neurons .5 to 15 m/sec

* -- on the finger surfaces

Table 1-1: Specifications for the Human Sensory System

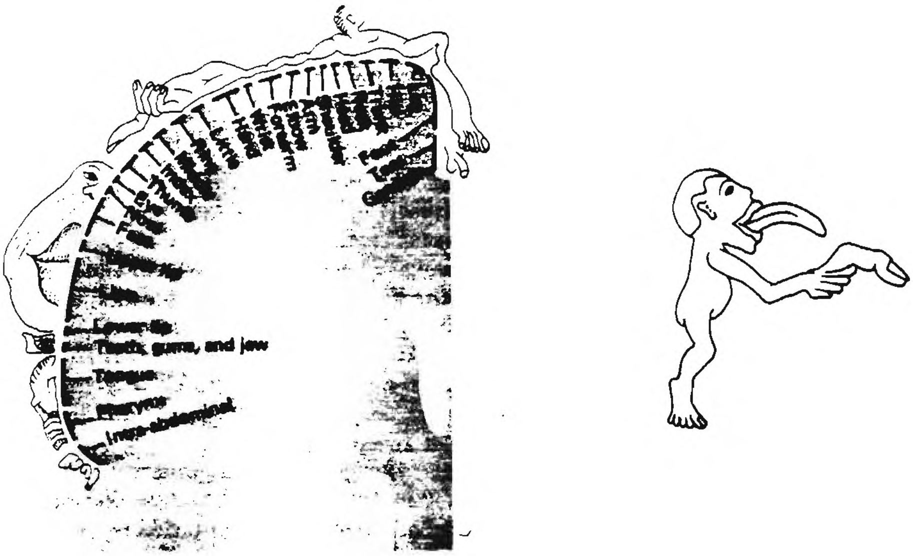


Figure 1-2: The Sensory Homunculus

lesson to be acknowledged by the developers of active mechanical manipulators is twofold. First, the level of complexity in human "touch" systems is prohibitive in terms of present technology, and second that the incremental understanding of the environment provided by such a system is manifold.

2. Tactile Sensor Technology

A manipulation system implemented in hardware will most likely require all the same data identified in the human haptic system: position, orientation, velocity and forces. The proprioceptive data is necessary for the low-level control of the manipulator, so the emphasis here will be on the acquisition of the tactile data resulting from an interaction with the environment. The technology associated with tactile feedback is extremely diverse, ranging from simple sensors that simply signal contact, to artificial skins that attempt to provide information about the mechanical strain at a contact as well as the thermal conductivity of the environment. This section will discuss some of the methods employed to provide this sensory information, and the problem of object recognition via tactile data.

2.1. Methods of Tactile Sensing

Before we begin to examine the various incarnations of the tactile sensor, let us establish criteria with which to discriminate among them. A primary issue in the selection of appropriate technology is the distinction between conformal sensing and the sensing of interface forces [15].

Conformal sensing produces information concerning the local profile or contour of the object. The incentive to develop such sensing techniques came from a desire to increase the utility of parallel jaw grippers. These grippers might, in the presence of uncertainty or when presented with concave objects, make point or line contacts with an object. A conformal "skin" on the gripper allows it to make a surface contact with the object and, therefore, provides a more stable grasp configuration. This approach can provide information useful in determining the objects identity [51], but is not directly useful in the determination of interface forces. Moreover, if we were to propose a conformal sensor which consists of an elastic medium whose thickness is measured by resistivity or time of flight, and load the sensor with tangential forces at the contact point, we would expect the elastic medium to deform tangentially as well as in the normal direction. The result is an object profile which may not resemble the actual object at all. For these reasons, when the objective is a system capable of grasping, recognition, and manipulation, it is preferrable to sense the contact forces directly.

Force sensing provides more pertinent information to a grasping and manipulation controller. As was mentioned above, a compliant covering improves the nature of the contact by spreading over the surface of the object. Furthermore, the covering serves to protect force sensing hardware underneath. It is worth mentioning at this point, that state of stress beneath an elastic medium is linearly superimposable, while the deformation is not. These observations allow the state of stress beneath a compliant skin to be modeled. The ability to distinguish the difference between planar surface contact and vertex contact has been demonstrated [15].

Other parameters of contact have been acknowledged to be useful in the control of manipulation hardware [24]. The *spatial resolution* realizable by any particular sensor defines the segment of the environment to which it might successfully be applied. While there are applications for sensors with very high spatial resolution, typical manipulation tasks call for resolution on the order of 1-2 mm, or roughly that of the human skin. The *sensitivity* and *dynamic range* vary from sensor to sensor and must be selected appropriately for each task. Ideally, touch sensors should be stable, monotonic, and repeatable. *Hysteresis* in a sensor implies that its output is not only a function of the mechanical input, but also on the recent history of inputs. The human touch apparatus is fairly hysteretic, but remains quite useful. The engineering approach to integrating tactile feedback into a manipulation controller decidedly prefers nonhysteretic sensors. The *frequency response* of the sensor may or may not be critical in the design of a tactile system. Some contact parameters require relatively high frequency signal content (i.e., slip detection or active texture analysis), but the lower limit on frequency response is often the access loop time in the control software. Last, but not least, the designer must consider the means of *addressing* the tactile "patches" and make room for the electrical connection from sensor to controller. The *number of wires* needed to access an array of sensors varies as a function of the technology used and the scheme employed to address the sensor patch.

The most straightforward tactile sensor is the binary contact switch. This sensor can be configured as an array to provide simple binary contact images, but does not provide useful force information. It is more commonly used to signal the controller that the manipulator has reached a known set point or is approaching the extent of its safe workspace.

Since we are interested in measuring interface forces, it is natural to consider strain gauge technology to measure orthogonal strains and to reconstruct the 3-D state of stress. This idea has been used inside of hemispherical fingertips to determine the point of contact with the object [62]. The approach is of little use in tactile arrays, however, since the resolution achievable is insufficient for most applications.

Conductive elastomers have been used extensively in the design of tactile sensors [10, 23, 24, 29, 58]. Since it is desirable to cover the tactile system with some type of compliant layer, it might initially appear advantageous to use a conductive rubber, a doped rubber, or a conductive foam to act both as protective skin and pressure transducer. These materials rely on the property that predictable changes in the resistivity of the material result from local deformations. However, the currently available materials are hysteretic and doped materials are generally not very rugged. Moreover, low sensitivity, noise, drift, long time constants, and low fatigue life make this sensor technology somewhat deficient.

Hillis [29] addressed these limitations by proposing a sensor illustrated in Figure 2-1

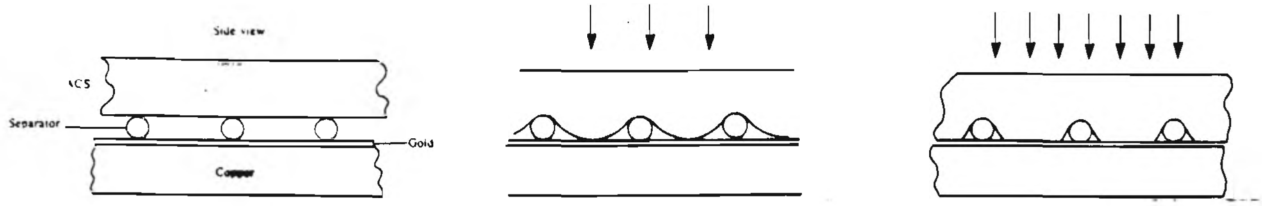


Figure 2-1: The Elastic Contact Resistance Sensor

The sensor employs a conductive silicon rubber (ACS) which deforms around the separator and contacts an electrode under an applied pressure. Increased pressure loading causes increased surface contact between the silicon and the electrode. The contact resistance is then inversely proportional to the applied pressure. The signal output of the sensor is proportional to the contact resistance rather than the point-to-point resistance in the silicon material. This implies that the elastic material can be selected to improve its elastic properties, without regard to the hysteretic conduction properties. Moreover, the separator can be designed to produce the correct sensitivity, resolution and dynamic range for the specific application. Hillis constructed an array of 256 tactile sensors using this technology. The number of wires need to address the array is reduced to a manageable level by accessing only rows and columns as depicted in Figure 2-2.

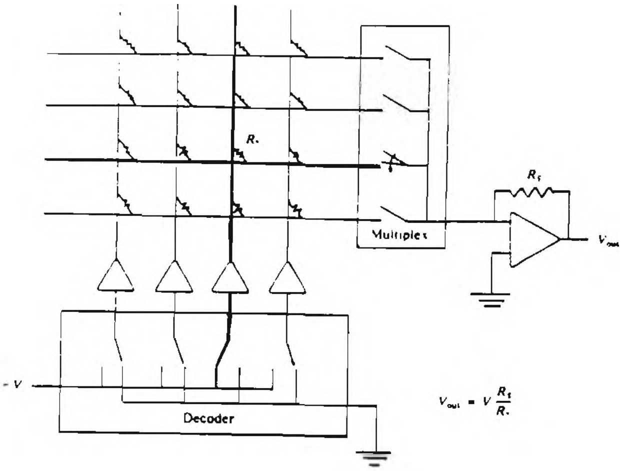


Figure 2-2: Addressing a Tactile Array

The column of interest is supplied with a known voltage while the other columns are grounded. The rows are then brought to ground by injecting the proper amount of current to offset the current produced by the active column. The value of the contact resistance at a specified row and column is then inversely proportional to the injected current. Hillis reports that an array of 256 tactile cells so addressed produces a cable of 32 wires resulting in a cable diameter of less than 3 mm.

Raibert [58] developed an analog to the Hillis sensor by incorporating VLSI local processing and tapered separating spaces to produce a "smart" sensor. A representation of the redesigned separator cell is shown in Figure 2-3. A prototype chip using 48 tactile cells in a 6X8 array was constructed with 15 electrodes per cell to produce 4 bits of pressure output per cell. Using serialized input and output data, the full scale prototype (that is on the drawing board) will incorporate 200 tactile cells with a 1mm spacing driven by only 5 wires: power, ground, clock, data-in, and data-out.

Optical technology has been found to be useful in the construction of tactile sensors. One such application involves the shuttering of a light beam by the contact deformation [8, 59]. The sensitivity, and dynamic range of such a sensor can be changed without altering the optical transduction. It would, however, be difficult to construct a high density array of these sensors and to transduce the three dimensional state of stress.

Another optical tactile sensor is proposed by Begej [4]. Here, a tactile "image" is generated using the frustration of total internal reflection. The effect is the same as the effect of touching the sides of a glass

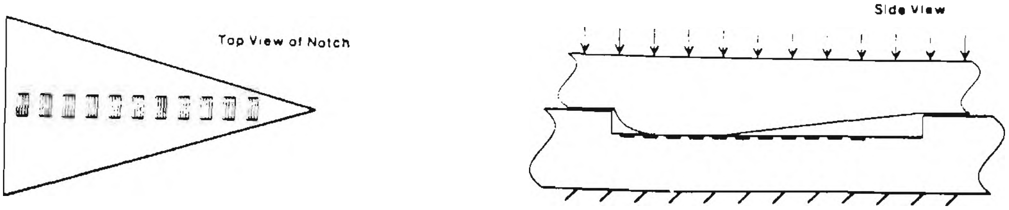
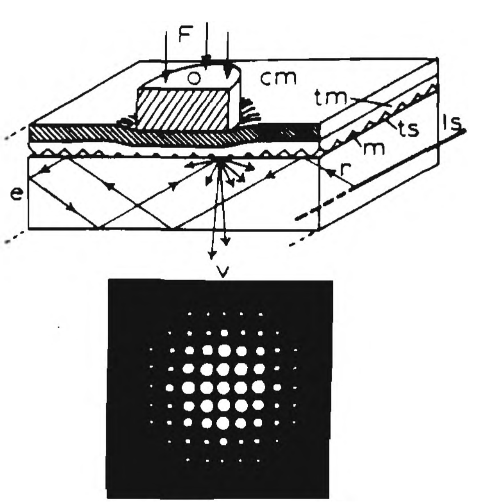


Figure 2-3: Raibert's VLSI Tapered Tactile Cell

of water, while looking down into the glass. The firmer the grasp on the glass, the more of an image they produce on the otherwise silvery glass surface. A schematic of Begej's transducer is presented in Figure 2-4.



F - applied force
o - round object
cm - cover membrane
tm - transducer membrane
m - microtexture on transducer membrane
ts - transduction surface (frustration of total internal reflection occurs here)
e - reflective edge
ls - linear light source
r - typical light ray
v - position of viewer
iv - image seen by viewer

Figure 2-4: Begej's Optical Tactile Sensor

An applied pressure on the transduction membrane causes more of the textured surface to contact the transparent medium and creates an intensity image of the state of stress in the material. Begej's implementation conducts this image away from the contact site by way of optical fibers and then displays it with a camera. This approach fails to relay information about tangential contact forces and is not yet suitable for application to the fingertips of a dextrous manipulator but is the object of considerable research.

Capacitive tactile sensors have been developed on the premise that capacitance is a function of the dielectric constant of the particular material as well as the thickness of the dielectric. With this in mind, a sensor can be visualized which produces a capacitive impedance output in response to a contact deformation [6]. Boie suggested a sensor which is presented in the Figure 2-5. The concept is directly analogous to the conductive elastomers presented earlier, except that capacitive systems should be faster and less noisy. Futhermore, materials which exhibit good capacitive properties generally also

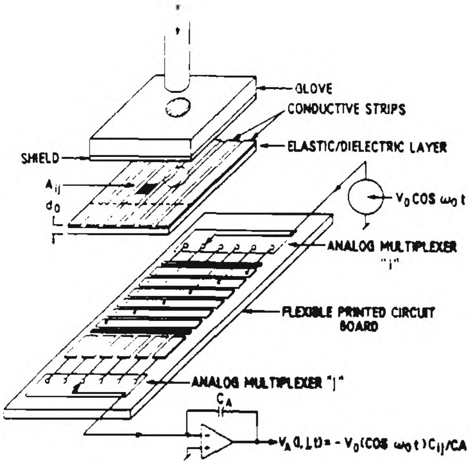


Figure 2-5: Boie's Capacitive Tactile Sensor

exhibit good mechanical properties; such is not the case with conductive elastomers. Note, however, that this approach to sensing is very strongly dependent on external fields, specifically, those produced by the object being handled.

Magnetostrictive materials may similarly be exploited to transduce contact. These materials are characterized by the change in their magnetic fields in response to an applied load. Luo *et al.* [47] have demonstrated a touch sensor based on these principles. The effect is a transformation from a magnetically isotropic material to a magnetically anisotropic volume of material in the presence of a load. The application of cleverly oriented induction coils may then transduce an applied force as an induced voltage. A sensor was fabricated into an array of 256 tactile cells with a spacing of 2.5mm that demonstrated good linearity, low hysteresis, good dynamic range, small thermal drift effects and good sensitivity. The sensors are, however, sensitive to external fields as were the capacitive sensors and are therefore limited in utility.

Piezo- and pyro-electric transduction has been shown to be potentially useful in many tactile sensing applications. Piezoelectric materials respond to mechanical deformation by producing output voltage potentials. Similarly, pyroelectric materials respond to heat fluxes by generating induced voltages. A sensor was constructed that utilizes both of these properties in an attempt to create more than simply a force transducer, but more ambitiously, to emulate human skin [3, 10]. The design is interesting in that it addresses very many of the components of the signal content mentioned earlier in our discussion of the human tactile system. The system is exemplified by the schematic presented in Figure 2-6. The material PVF2 (polyvinylidene fluoride) is unique because it possesses both piezo- and pyroelectric characteristics. Figure 2-6 shows a composite structure which is intended to provide an extremely large bandwidth response as well as measuring the relative thermal conductivity of the object being touched. Three dependent signals are produced by the sensor. The dermal layer of PVF2 is used to transduce contact forces. The structure developed responded to frequencies up to 500 Hz and was limited by the resonant frequency of the composite structure; it does not, however, respond well to DC forces. The layer of conductive rubber on top of the dermal PVF2 is included to add this DC capability. The resistive paint in the structure is used to provide a reference temperature (98.6° F) to the epidermal PVF2 layer.

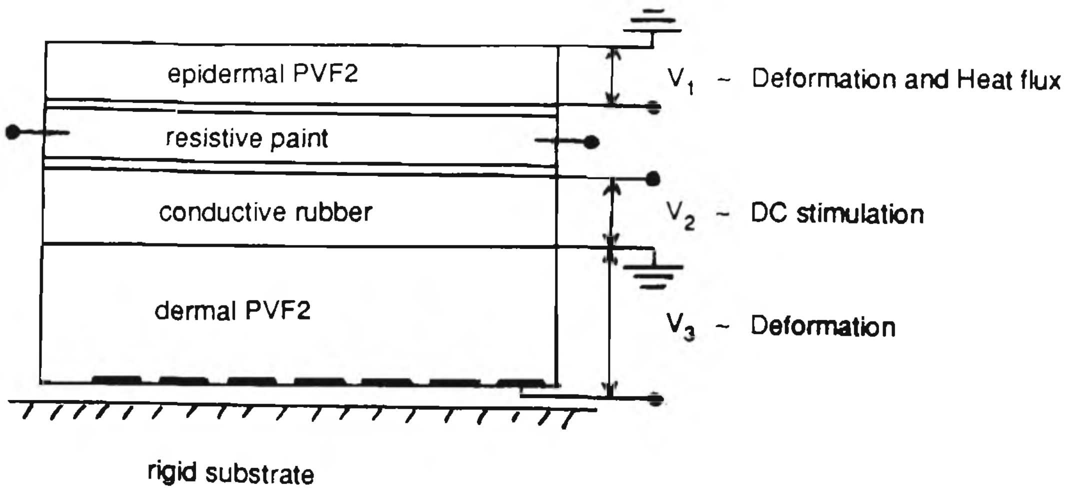


Figure 2-6: The Dario *et al.* Artificial Skin

The signal output by this layer is then a function of both the heat flux and deformation due to a contact with the environment. The conductive rubber beneath the resistive paint effectively insulates the dermal PVF2 layer so that the signal may be (approximately) separated. The potential of such a design is quite good since it contains information that is useful in the human manipulation system. However, in practice the sensor produces signals that are quite cryptic due in part to the inability to entirely separate the thermal and deformation induced potentials.

2.2. Machine Perception with Tactile Information

The perceptual capabilities of the tactile system in human beings are familiar to everyone; the extent that these contact stimuli effect our models of the environment, however, has been the object of much discussion. The tactile sense of space is a result of not only tactile stimulus, but involves the integration of tactile, visual, and kinesthetic signals to the brain. It has been noted [5] that in the absence of kinesthetic experience due to congenital or acquired paralysis, the tactile model of the environment is impaired as reflected by stimulus localization for example. The degree to which a sufficient, spatially coherent model of the environment can be constructed in the absence of visual sensory data is also suspect. It is, however, clear that biological systems (man in particular) can model the immediate (i.e., within its workspace) environment quite well in the absence of visual input and can recognize and discriminate between familiar objects.

The relative contribution of the various signal modalities in the human hand produces a very rich and diverse array of tactile sensation. The so called *touch blend* [63] of temperature, pressure, and vibration signals permits the distinction between wet, slimy, greasy, syrupy, mushy, doughy, gummy, spongy or dry elements of the environment.

The role of movement, or active exploratory strategies in touch has been acknowledged to be critical to the efficient utilization of tactile information [1, 10, 11, 18, 25, 29, 63]. Hardness, texture, compliance and surface features such as contour, vertexes and edges are available to the tactile sensor which is capable of "scanning" its local surroundings. There has been, and continues to be some interest in treating the analysis of tactile information in a manner analogous to vision processing, where tactile images are processed to yield tactile discriminators. These techniques are useful only for objects of a scale similar to or smaller than the tactile array. For this reason, the discussion here will focus on the collection of spatially distributed low level tactile features by active exploratory strategies.

The components of the active search in the absence of *a priori* information about the environment or other sensing modalities might proceed as follows [18]. The first step involves a gentle rapid probing contact with the environment. Immediate nearby objects are classified on a pain or thermal basis. After potentially harmful objects are identified, a more deliberate exploration of the object of interest is begun. The shape of the object is examined by determining the spatial distribution of faces, corners, edges and holes. The object may be grasped and moved, providing perhaps relative weight, center of mass, hardness, and thermal conductivity parameters. More geometrical information can be ascertained by excursions of the finger tips with variable contact pressures to determine surface details such as texture, size, shape, and notable areas of curvature [11, 65]. The parameters are in some way interactive with a knowledge driven process which determines the object's identity and its influence on the rest of the environment.

Ellis [11] cites a simple application of active tactile exploration involving pressure modulation. Here, it was noted that estimates of edge radii and object compliance can be obtained by modulating the pressure applied to the object's surface. Ellis also describes the use of passive tactile information to discern the texture of various surfaces [12]. This approach requires high spatial resolution, whereas, an active texture analysis requires high bandwidth. Considering the hardware constraints of the tactile system (packaging and cabling), it seems that once again, the active texture analysis is more appropriate.

Active Touch

Hillis [29] describes the difference between an analytic or bottom-up approach, such as that employed by vision algorithms, and the top-down or knowledge driven approach which seems more appropriate in tactile recognition systems. Vision systems acquire an image and then process this data. The technology which supports vision demands this type of an approach. Tactile systems, however, acquire small amounts of data at a time and are more appropriately used in an active, knowledge driven manner. The active approach interacts well with an evolving representation of the environment and is an efficient means of identifying objects given a model base.

Schneiter [64] demonstrates the active approach to recognition and localization in a 2-D, planar domain using an implementation of the interpretation trees proposed by Grimson and Lozano-Pérez [19]. The procedure involves a representation of the object which consists of tables of constraints for distances, normals and directions between faces. Models of the object(s) are used to create a tree of all consistent interpretations of the data already collected. The resulting interpretation tree is pruned by generating tactile sensor trajectories which most efficiently discriminate between the competing interpretations.

It was noted earlier that the tactile model or sense of the environment in human beings is a function not only of tactile and kinesthetic information, but is also integrated into a spatial representation involving visual information. Allen [1, 2] makes use of this anthropomorphic example by designing a recognition/localization system which combines a passive vision system with an active tactile system to produce surface and feature representations of objects. The system he describes consists of a stereo pair of CCD cameras and a tactile "finger." The tactile sensor contains 133 tactile patches (conductive rubber) distributed over a structure roughly the size and shape of the human index finger but with no articulation. The finger is positioned within the workspace by a six degree of freedom PUMA robot arm.

The vision system uses a stereo pair of cameras to grow a sparse set of 3-D points located on the boundary contours of closed regions in the image. Rather than push the computationally intensive vision system, the tactile system is employed at this point to ascertain the objects surface character.

The tactile system is dispatched by a hierarchically structured controller. The highest level determines from the visual image which areas of the object merit further attention. When a region is identified, the intermediate level of the controller initiates an exploratory procedure. The inputs to this process is a least squares plane and normal derived from the 3-D boundary contours provided by the vision system. The intermediate level of the controller then determines an appropriate approach vector and orientation for the tactile sensor. Subsequent contact with the object fills in additional surface information, or instigates the tracing of another boundary contour if a cavity or hole is encountered. The discrete 3-D data is combined into a surface description using a bicubic interpolation creating a composite surface which is curvature continuous (C^2 continuity). Figure 2-7 is a sequence provided by Allen [2] representing the evolution of a surface description for a pitcher. The final figure in the sequence is the approximate composite surface resulting from only four surface patches (it is derived from the center figure above it). The representation of the object is quite good already, but the beauty of the approach is the potential of using task constraints to further refine the surface only in those regions of interest. The work done by Allen is notable not only because it integrates vision and touch sensing, doing so without pushing the capabilities of either technology, but also because it provides a framework for the efficient, knowledge driven perception of the environment.

3. Machine Manipulators

Many different manipulators have been developed with a variety of configurations and with correspondingly diverse capabilities. Industrial flexible machining processes require highly constrained manipulators (fixtures or conformal clamps) with few degrees of freedom capable of transmitting large amounts of power to the stock. These conditions preclude the consideration of truly dextrous manipulators on two counts; first, the stock is regular and assumes a limited number of geometries, and therefore, does not require dexterity, and second, the degree of dexterity and the power transfer capability vary inversely. The discussion here will focus on those applications such as light assembly which require moderate power transfers and slight compliance. These operations are facilitated by the dextrous manipulator which can sense the position and orientation of the object it is handling.

3.1. Specifications for Mechanical Grippers

A great deal of industrial processes could be entirely supported by machine manipulators with two or three fingers equipped with tactile sensors. In fact, there are estimates that 80% of industrial assembly tasks could be accomplished using this relatively simple technology [26].

The workhorse of the mechanical end effectors is the two parallel jaw gripper. Given an appropriate set of objects these grippers are capable of manipulation and may be used to support object recognition. Generally, the first application of prototype tactile sensors is the conformal mapping of small objects such as washers, nickels, and regular shapes such as cylinders and rectangles while strapped to the flat gripping surfaces of the parallel jaw gripper. In addition, given the flat geometry of the gripper, it is natural

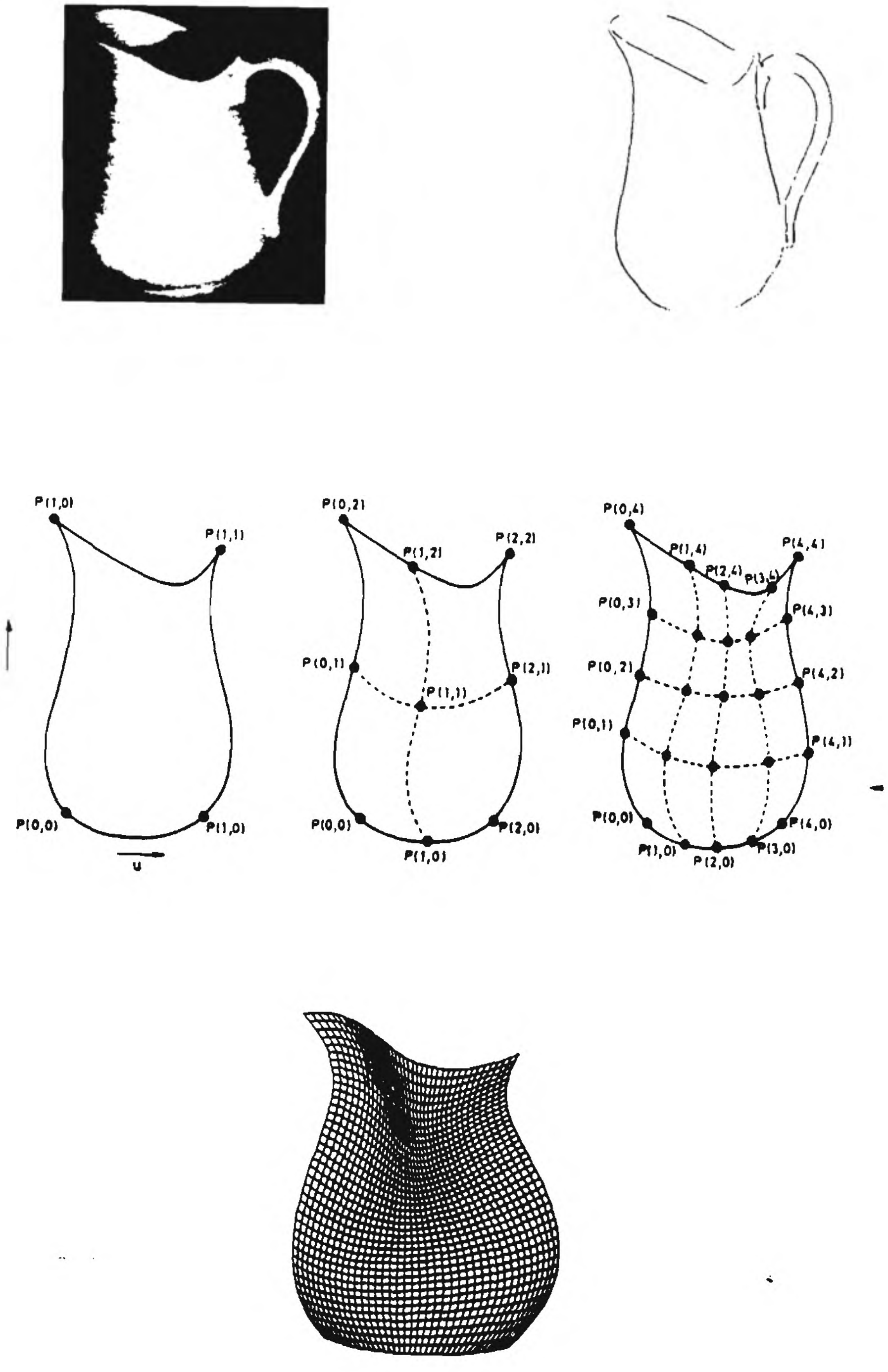


Figure 2-7: Allen's Passive Vision/Active Tactile Recognition Procedure

to apply conventional image processing techniques to extract tactile features such as vertexes or line contacts. The focus of this paper will be on the dextrous manipulators which benefit more significantly from the acquisition of tactile data.

It is suggested that three fingers may be necessary to reproduce the predominate grasps of the human hand [25]; others point out that four fingers allow a grasping redundancy, and therefore, exchange between fingers. Why human beings possess five fingers is matter of much conjecture. The pectoral fins of fish also contain five "finger" bones, which implies that there is no logical connection between the grasping task and the number five. The control system for the human manipulation machinery does, however, make use of this redundant finger. For example, a finger not involved in a grasp might perform an active search of the object or the environment; assembly compliance can be addressed by actively sensing the relative orientation of the part and the sub-assembly with which it is to be mated. The number of joints per finger must likewise be a design parameter. The following section presents some of the notable manipulators that have been developed for use in research. To be comprehensive in this regard is an ambitious undertaking, therefore, a few representative designs will be discussed.

3.2. Representative Hand Designs

Okada [53] developed an industrial object handling system which consisted of a five degree of freedom arm/wrist coupled with a three fingered, eleven degree of freedom hand. The hand itself is a rough model of the human hand, addressing such grasping primitives as wrapping, pinching, picking, gripping, and searching. Each finger has four degrees of freedom, while the thumb has three degrees of freedom as shown in Figure 3-1.

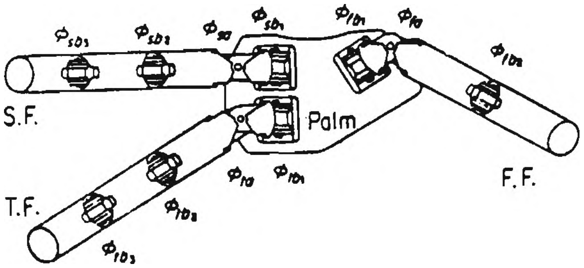


Figure 3-1: Structure of the Okada Manipulator

The arm was included to produce a large workspace for the manipulator and to improve the possible pre-grasp orientations. To minimize the weight of the hand and thus increase its maximum payload, the motors used to drive the hand are located in the trunk of the device and transmitted through wire sheathed cables approximately 1.7 meters. As a result, there are significant frictional and elastic effects which degrade the response character. The finger control consists of a hybrid position/torque servo implemented in hardware. The control scheme is selected by observing the movement of the finger in response to a command input. The transition between position and torque control is smoothed somewhat by varying the command voltage so as to maintain the error signal (the difference between the command and the feedback) at a constant value. The hand demonstrated an ability to stably grasp simple objects by defining one side of the opposing grip as position control and the other as force control. It reports an ability to successfully grasp and hold objects up to 500 grams in weight, but moved at an extremely low speed as indicated by its paltry 0.06 Hp power consumption.

Lian *et al.* [44] developed an anthropomorphically motivated hand which was intended to reproduce several important human grasps, among these:

a) tip opposition - tip of index finger to tip of thumb,
b) lateral opposition - side of index finger to tip of thumb,
c) palmar prehension - fingers and thumb wrap around a cylindrical shape,
d) spherical prehension - fingers and thumb wrap around a spherical shape, and
e) digitio-palmar opposition - fingers alone wrap around an object.

The design of the manipulator involved the kinematic modeling of the mechanism and the graphical simulation of the above grasps. The resulting three-fingered design is a model of the human thumb, index, and middle fingers. Each finger has three degrees of freedom. The proximal joint of the fingers (the metacarpal-phalangeal joint) operates only in adduction-abduction about an axis perpendicular to the axis of the two remaining interphalangeal joints. The thumb is modeled similarly except that the proximal joint is inclined at 60 degrees to the palm, while the fingers are perpendicular to the palm. A schematic of this configuration appears in Figure 3-2.

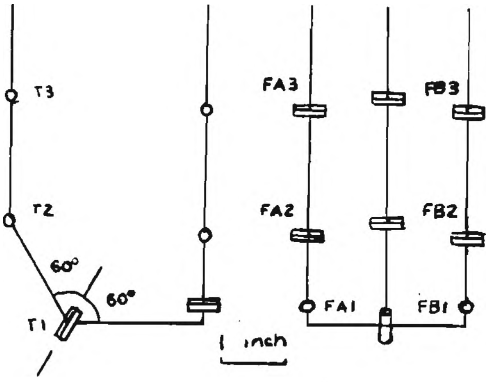


Figure 3-2: The Kinematics of the Lian *et al.* Manipulator

The finger tips of the manipulator are fitted with replaceable hemi-spherical friction tips which approximates a point friction contact. The fingers are actuated using DC motors driving stainless steel cables inside of wire wound sheaths. This means of power transmission introduces considerable elasticity and non-linear friction due to the sheathing. The design incorporates no tactile sensing at this point and requires that grasping forces be determined by measuring cable tensions and joint positions. This limits the grasping options unfortunately, to categories (a) and (b) above. This type of grasping force transduction leads to ambiguous results if the object contacts the finger in more than one position.

In contrast to the anthropomorphic approach to manipulator design, Hanafusa *et al.* [22] developed a three-fingered hand capable of implementing an analytical grasping algorithm. The resulting design is not terribly dextrous, but is interesting because it introduces the concept of grasp stability, which we will discuss further in a later section. A schematic of the hand gripping an object is presented in Figure 3-3.

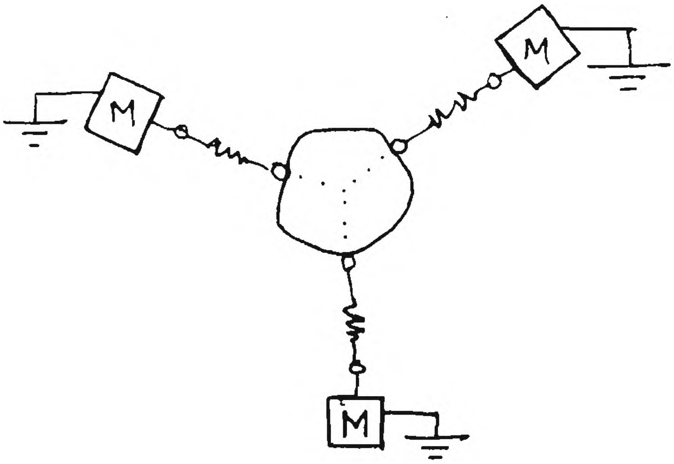


Figure 3-3: Schematic of the Hanafusa *et al.* Manipulator

Each single degree of freedom finger is positioned 120 degrees from the adjacent fingers and is actuated by a step motor through a coil spring. The finger force is measured by a potentiometer inside the coil spring. The displacement of the finger tip is measured by a second potentiometer. This arrangement allows the control of the normal gripping force of each finger. The contact point is on a roller to eliminate any tangential components of the grip. The potential function consists of the sum over all fingers of the product of the finger force and the differential movement integrated over the path from the initial state to the stable prehension state, plus the gravitational potential. The potential is also the elastic strain energy of the finger's coil spring. The contention is that when the prehension state reaches a local minimum, it is stable, that is, an external force which displaces the object from its command position can be overcome by actuation of the fingers. Since the deflection of the tip of the finger is measured, a control system can modulate the apparent stiffness of the manipulator by driving the finger motors synchronously with finger tip movements. In practice, the hand requires the integration of a vision system capable of extracting the object silhouette(i.e., as in [7]) and positioning the hand close to a local minimum. The hand's dexterity is limited; however, it has demonstrated an ability to perform many industrial manipulation tasks.

The Stanford/JPL hand was motivated not by anthropomorphic considerations, but by kinematic and control issues [60, 61]. The parameters used to evaluate the effectiveness of the manipulator were; the number of fingers, the number of links per finger, and the type of contact between finger and object. Contact types considered included those presented in Table 3-1

The analysis [60, 61] involves the classification of proposed finger combinations based on their ability to:

1. exert arbitrary forces or impress arbitrarily small motions, and
2. entirely constrain the object by fixing all the active joints.

REMAINING DOF	TYPE OF CONTACT
0	Glue
1	Line contact with friction, revolute joint
2	Soft finger
3	Point contact with friction, plane contact without friction
4	Line contact without friction
5	Point contact without friction

Table 3-1: Salisbury's Contact Types

Salisbury evaluates a proposed mechanism by employing a number synthesis[3] to speak about the mobility and connectivity of the hand/object system.

Mobility is the number of independent parameters needed to completely specify the state or configuration of the mechanism. The mobility is determined by a modified form of Grübler's formula:

$$M \leq \Sigma f_i + \Sigma g_i - 6L$$

$$M' \leq \Sigma g_i - 6L$$

where:

M = mobility of the system with joints free,
M'= mobility of the system with joints locked,
f_i= degrees of freedom of i^{th} joint,
g_i= degrees of freedom of i^{th} contact, and
L = number of independent kinematic loops in the system.

The inequalities in the above equations reflect the possibility that some of the contacts may produce redundant constraints on the object.

Connectivity is the number of independent parameters needed to specify the relative position of two bodies. In this case, the bodies considered are the palm and an object. Connectivity is determined by fixing the two bodies and computing the difference between the system mobility and the mobility of all sub-chains connecting them. In order for the hand to impart arbitrary motions and forces, the connectivity of the active mechanism must be six (for general 3-D motion). For the hand to completely constrain objects, the connectivity of the fixed mechanism must be less than or equal to zero.

Salisbury considered 600 candidates with one, two, or three fingers with three links per finger, where all the contact types for a given hand are the same. More complex hands (with additional links or fingers)

---

[3] number synthesis - a design methodology focusing on the number of links and joints to accomplish the purpose of a mechanism [55]

were not considered and it was noted that several acceptable designs were thus dismissed. Immediately discarded were designs that required five degrees of freedom per contact since this corresponds to a frictionless, point contact and severely limits the usefulness of the resulting manipulation system. By these criteria, the best resulting design was one with three fingers, three links per finger and three degrees of freedom prehension contacts. This type of contact is achieved by point contacts with friction or planar contacts without friction.

The final design was based on a number of analytical and intuitive procedures. A simulation of the hand was used to optimize over a user selected parameter space. Among these are the relative finger locations, link lengths, and joint range of motion. The model computed a performance index based on three fingered grasps using fingertip prehension. While power grasps were not explicitly evaluated, the final design was imbued with features thought to be desirable in this respect, among these: relative finger placement and palm area. In addition, the relative orientation and placement of the fingers was influenced by the location of so called isotropic points in each finger's workspace and superimposing these loci in an area over the palm. Isotropic points are positions where the mechanism is able to impart accurate forces to objects which contact its fingertips. These isotropic points are locations in the workspace that minimize the condition number of the Jacobian matrix and thus minimize the error propagation from input torques to output forces. The locus of isotropic points for the finger configuration described above is shown in Figure 3-4.

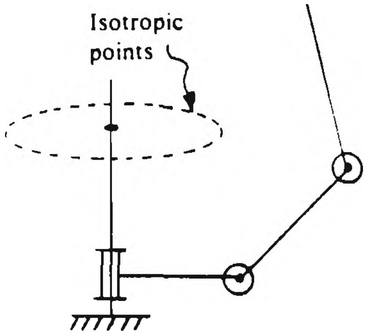


Figure 3-4: Locus of Isotropic points for a Three Joint Mechanism

The hand design superimposes the loci of the isotropic points of the three fingers in a suitable area over the palm. A schematic of the resulting hand design is presented in Figure 3-5. The Stanford/JPL hand is actuated by a tendon scheme using cables with tension sensors. Four antagonistic tendons control the three joints in each finger. Teflon coated tendons are routed through conduit and are driven using motors and gear trains mounted in the forearm. A servo loop receives as input the cable tension near the fingertip, motor position and velocity to estimate the joint angles and velocities. The effects of friction and elasticity can be mitigated by sensing cable tensions close to the point of application.

The Utah/MIT hand [37, 38] is perhaps the most ambitious effort towards a truly anthropomorphic

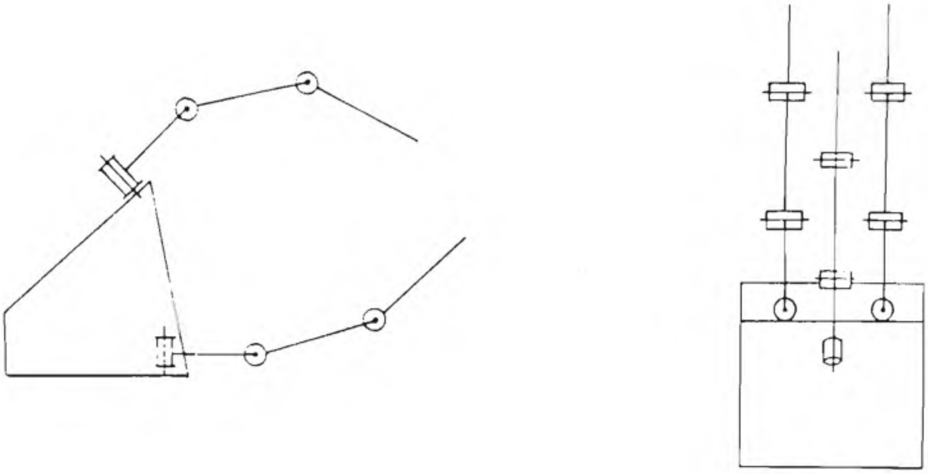


Figure 3-5: Schematic of the Stanford/JPL Manipulator

manipulator. Except for the fact that it has three four DOF fingers, one four DOF thumb, a three DOF wrist, and link length modifications deemed necessary for routing the tendons, this design is a good facsimile of the human hand.

One of the distinguishing features of the design paradigm of this hand was that it, from the outset, was intended to be a model of the human hand. The reasons for this approach are:

1. The human hand is an existence proof that a hand with this geometry, given a suitable control scheme, is a powerful manipulation device,
2. research into the nature of grasping and manipulation with such a mechanism would permit the researcher to correlate the performance of the mechanical hand with its human counterpart, and
3. such a design would also be quite easily adapted to teleoperation.

The hand is actuated by extremely fast pneumatic cylinders through tape tendons. Both these systems were developed specifically for use with this dextrous hand.

The resulting pneumatic actuators are fast, low friction, and can generate relatively high forces. They incorporate a pressure control valve so as to minimize the effects of compressibility in the working fluid. The resulting system acts as a mechanical force source with no spring constant and very little mass and damping.

The 19 DOF hand is actuated using a 2N tendon approach, which implies a system of 38 independent tendons and actuators. The hand is actuated remotely through the tendons which reduces the payload weight of the hand, and makes space for peripheral sensor systems.

The resulting actuation system is actually faster than the human hand, while providing about the same forces. Since each joint is actuated by two pneumatic actuators in an antagonistic arrangement, each joint's stiffness is controllable. In addition to these human-like mechanical qualities, the hand was also imbued with certain anthropomorphic reflex qualities that will hopefully increase its effectiveness as a manipulation device. The stiffness or the configuration of the hand is modified based on the interaction of the hand with the environment. The Utah/MIT hand senses the interaction forces as tendon tensions so that the initial phases of a grasp might be directed by very low level reflexive movements. Specifically, the hand implements two reflex motions which have been observed in the human hand:

1. proximal stiffening: a contact with the environment causes the proximal joints to stiffen, and
2. distal curling: a contact causes all distal joints to curl about the already established contact point.

A schematic of the Utah/MIT hand and some of the anthropomorphic grasps that motivated its development is presented in Figure 3-6 and Figure 3-7.

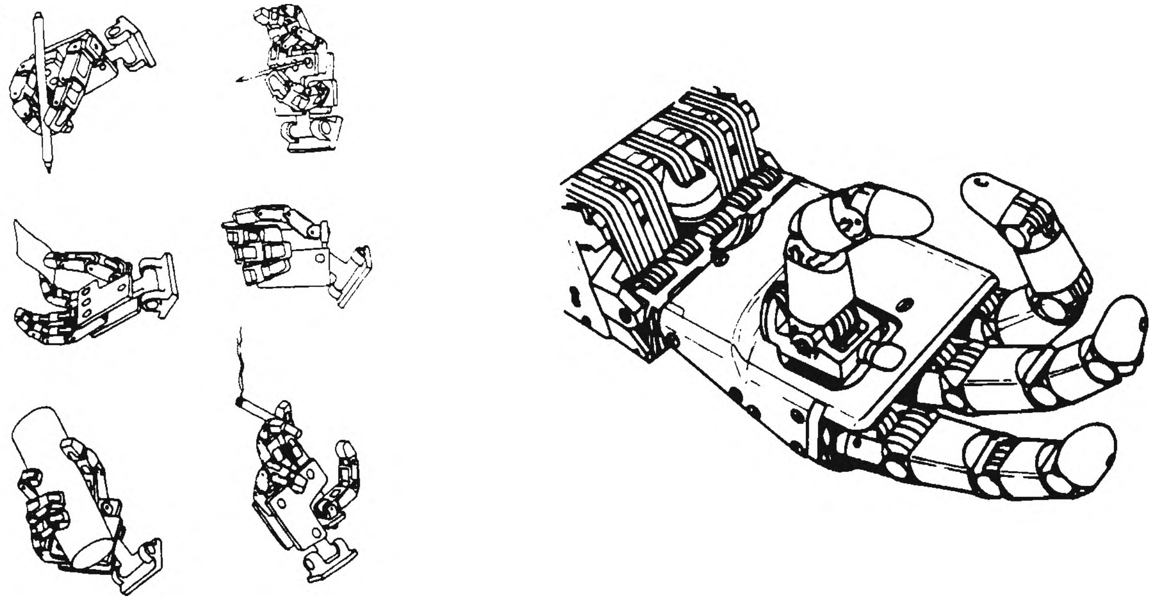


Figure 3-6: The Utah/MIT Dextrous Hand

4. Controlling the Machinery

4.1. A Brief History of Manipulator Control Strategies

The ideal control scheme would be that which accepts commands such as: put object A into hole B, or, thread nut C onto bolt D. The execution of the command would consist of many small sub-tasks consisting of both commanded trajectories and commanded compliances/forces. The means of realizing this control strategy requires the control of both position or velocity, and forces.

Perhaps the first gripper operated by a computer under a feedback control strategy was demonstrated by Ernst [13] in 1961. It was capable of performing simple manipulation tasks using tactile feedback to verify the presence or absence of an object. Since this early work, many investigators have sought to improve the behavior of the manipulator that is in contact with the environment. Simple position control when dealing with a rigid environment in the presence of uncertainty proved unsatisfactory in the vast majority of assembly operations. Some type of compliance was needed to accomplish many manipulation tasks.

see attached photographs

Figure 3-7: The Utah/MIT Dextrous Hand with Remotizer and Actuator Package

Whitney in 1977 implemented an admittance matrix model to predict the manipulator velocity in response to external forces [67]. Force, position and velocity sensors were used to make small corrections in the trajectories of contacting parts. This work demonstrated the idea of manipulator impedance (or perhaps more accurately, admittance) and allowed contact forces to produce small deflections in the grasped part which in turn avoided jamming parts together. The result was a compliant control methodology that was capable of peg-in-hole assembly tasks.

Similar efforts to imbue the manipulator with a compliant character have defined orthogonal sub-spaces within which either position or force may be controlled. Paul *et al.* in 1976 implemented this strategy by selecting the manipulator joint that was most closely aligned with a command force vector and imposing the appropriate input force with that single joint [54]. The joints not involved with the force command were under position control.

Raibert *et al.* in 1981 combined force and position trajectory constraints by allowing the specification of the sub-space within which position control is effected, while allowing force control in the remaining sub-space [57]. The components of the error signals in both force and position which map into a joint's workspace contribute to the feedback control of that joint.

Mason in 1981 notes that it is important to control position and force simultaneously in fine assembly tasks, and developed the notion of natural and artificial constraints [49]. Tasks are modeled by a C-surface (constraint surface), to which forces may be applied along the normal and positions controlled along the tangent. Mason described a manipulation strategy involving extremely compliant guarded moves combined with task controlled compliant motion. A task is compiled as a sequence of motions/forces and projected on the real world, gross errors in the task model are then actively eliminated.

Salisbury in 1982 approaches the problem in a slightly different way [61]. He suggests, as does Mason, that task defined stiffness/compliance be established, but instead of executing a sub-task and then evaluating its accuracy, proposes that task constraints be established using the position and force measurements and adjusting stiffnesses accordingly. Here, the environment is actively sampled along 6 orthogonal axes so that contact forces resulting from the motion may be determined. Knowledge of the nominal control stiffness and the contact force were used to evaluate the environmental stiffness.

Geschke in 1983 demonstrated a rather unique implementation of the position/force controller in the form of his *Robot Servo System* or RSS [17]. The system is noteworthy in that rather than consisting of a sequence of independent manipulator actions, the instructions to the system are compiled into a set of independent servoed processes. A single instruction in RSS initiates a servo process which actively seeks its goal until either cancelled or redefined. A compliant sub-space may be specified which in this approach might change continually as the task geometry changes. Moreover, the programmer may specify the set of sensors employed by each servo process. The system employs position and force information from the robot itself, or data from an external vision system. Geschke demonstrates the system by performing a crank turning task where the force delivered by the hand is a function of the sensed position. The command consists of one servo command to the RSS. Another example employs visual tracking to perform the peg-in-hole insertion.

4.2. The Stable Grasp

To introduce the concepts involved in producing a stable grasp, consider the following problem posed by Kobayashi [40, 41] and illustrated in Figure 4-1.

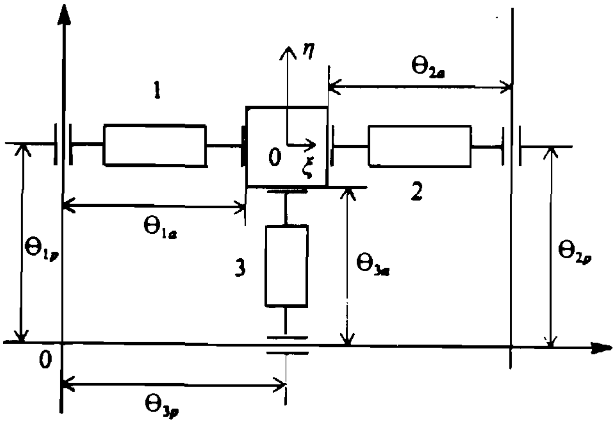


Figure 4-1: A Demonstration of Stable Grasp Analysis

Each finger in this 2-D gripper is active in one direction and passive (compliant) in the other. In order to maintain a stable grasp while the actuators move the object, Kobayashi develops the idea of the manipulation and free sub-spaces:

Sm - space in which all fingers remain in contact with the object and may actuate without violating the mode of contact of another finger, and

Sf - space or degrees of freedom remaining for the object when all actuators are fixed.

These spaces are constructed by intersecting the spaces associated with each finger. The grasp is entirely constrained and stably grasped if the rank of the Sf space is zero and may be manipulated in the space defined by Sm. These spaces can be directly deduced for the simple geometry presented; note that the object coordinates are related to the finger coordinates as follows:

finger #1:

$$\begin{Bmatrix}\partial\xi\\ \partial\eta\end{Bmatrix} = \begin{Bmatrix}1\\ 0\end{Bmatrix}\partial\theta_{1a} + \begin{Bmatrix}0\\ 1\end{Bmatrix}\partial\theta_{1p}$$

finger #2:

$$\begin{Bmatrix}\partial\xi\\ \partial\eta\end{Bmatrix} = \begin{Bmatrix}-1\\ 0\end{Bmatrix}\partial\theta_{2a} + \begin{Bmatrix}0\\ 1\end{Bmatrix}\partial\theta_{2p}$$

finger #3:

$$\begin{Bmatrix}\partial\xi\\ \partial\eta\end{Bmatrix} = \begin{Bmatrix}0\\ 1\end{Bmatrix}\partial\theta_{3a} + \begin{Bmatrix}1\\ 0\end{Bmatrix}\partial\theta_{3p}$$

The free space depends only on the passive degrees of freedom and it is possible to examine finger combinations to find a stable grasp. With the first two fingers:

$$S_f = \cap S_{fi} = R\left[\begin{Bmatrix}0\\ 1\end{Bmatrix} \cap \begin{Bmatrix}0\\ 1\end{Bmatrix}\right] = R\left[\begin{Bmatrix}0\\ 1\end{Bmatrix}\right]$$

Therefore, fingers 1 and 2 allow unconstrained movement in one direction (the y direction). Similarly, for three fingers:

$$S_f = \cap S_{fi} = R\left[\begin{Bmatrix}0\\ 1\end{Bmatrix} \cap \begin{Bmatrix}0\\ 1\end{Bmatrix} \cap \begin{Bmatrix}1\\ 0\end{Bmatrix}\right] = \left\{\varnothing\right\}$$

The above equation suggests that when three fingers remain in contact with the object, the object is fully constrained. Furthermore,

$$S_m = \cap S_{mi} = R^2$$

This analysis extends directly into three dimensions, the objective now is a free-space with rank zero and a manipulation space of rank 6. An extension of the concepts presented here allowed Kobayashi to define grasping conditions which permit the manipulation of the object using only the active degrees of freedom of the manipulator (i.e., fixed wrist and arm).

Fearing [14] states a stability criteria similar to that defined above. In his terms, a robust grasp is able to resist an arbitrary externally applied force without any displacement. The nature of the stable grasp is, therefore, a function of the type of contact between fingers and object. The analysis provided by Fearing considers only two fingers, but is easily extended to three or more.

The stability criteria can be decomposed into three requirements [14, 21]:

1. The object is in static equilibrium, there is no net force or moment,
2. all forces are applied within the cone of friction so that there is no slippage, and,
3. applied forces can be resisted by increasing the grasping forces and without moving the fingers.

The procedure for acquiring a part is more general here since it involves four phases; approach, initial contact, initial grab, and the stable grasp.

The approach phase of the grasp is perhaps the simplest conceptually, but may require substantial amounts of time. Hanafusa *et al.* [21, 22] suggested the implementation of a vision system to locate the objects and report the orientation so that a stable grasp may be computed. If this option is not available it may be necessary to perform a painstaking guarded motion search of the environment using tactile feedback. The search is performed using a very compliant joint control so as to disturb the object as little as possible at contact. *A priori* information of the object shape will be helpful in determining the configuration of the hand during the search which facilitates the post-contact grasp.

The initial contact with the object provides the first indication of its identity and orientation. The role of the initial contact is then to direct the subsequent grab and stable grasp. Parameters such as local normal and curvature can be deduced from active encounters between the object and the finger. The ability to perform these discriminatory tasks at this point is dependent on the geometrical design of the hand and the tactile capacity of the hand. It is not, however, required for the feature extraction mentioned to be performed at this point.

Once a compliant "collision" with the object is accomplished, the grasp algorithm endeavors to maintain this contact while guessing trajectories of adjacent fingers which are likely to produce additional contacts. Mason [50] was able to predict the behavior of planar objects resting on a plane while being pushed. A series of pushing paths can be useful in reducing the uncertainty of the objects position and orientation. Multiple contacts allow the motion of the object to be measured, or conversely, a force can be applied to the object and the resulting motion observed. In this way, the object may be grasped, or the recognizable features of the object may be extracted.

The final step is the modification of the contact to produce the stable grasp. Once again, Fearing and Hanafusa *et al.* have the same basic conception of a stable grasp, that is:

1. the object be in static equilibrium,
2. there is no slippage, and
3. that an externally applied force can be resisted by finger forces with a finite and controllable deflection.

To satisfy the no slippage condition, the initial grab must be modified so that each contact is transmitting forces within its cone of friction. The effect of multiple fingers is evident since the ease of satisfying conditions (2) and (3) is directly proportional to the number of contacts established in the initial grab. Citing, once again, the anthropomorphic example, it is quite common that the initial grab immediately produces a stable grasp. Fearing [14] discusses the two fingered grasp since this is a more universally useful technology, however, it also represents a worst case situation of a task more effectively accomplished by a dextrous manipulator. The no slippage condition applied to the two fingered gripper requires that the gripping forces be transmitted through two local normals. An initial grab which cannot satisfy this constraint will cause the object to slide or roll relative to the fingers until the grasp fails or is successful. During this process, either the object or the hand must comply. An object priority grasp produces a stable grasp without disturbing the object. To accomplish this grasp the contact must consist of low magnitude forces and high compliances relatively to some perceived frictional forces between the object and the environment. Ideally, the wrist compliance should be nearly infinite in three degrees of freedom. The fingers are controlled using the local normals to produce a two dimensional stiffness control.

A more brute force approach to grasping is termed hand priority grasp and consists of induced movement in both the object and the hand. The approach is similar, except the migration of the grasp relative to the object involves a displacement of the object.

The final stability criterion requires that the grasp can resist an externally applied displacement force. The analysis involves simply superimposing the grip force and an externally applied displacement force. The stability criterion is satisfied if the grip can satisfy static equilibrium conditions without violating the cone of friction of either finger. A two dimensional displacement requires three friction point contacts in general to meet this condition; however if the magnitude of the external force is kept low, two friction contact points are capable of resisting 2-D displacement. The deflection of the hand/object in response to this disturbance can be regulated by controlling the stiffness of the fingers.

This analysis is directly extendable to a three or more fingered hand and suggests an approach to manipulation [16]. The baton twirling problem can be viewed as a succession of stable grasps. For example, two fingers in a stable grasp can be perturbed by a third, producing a controllable deflection (in this case a rotation). One of the fingers involved in the original grasp is now released and repositioned in order to perturb the grasp produced by the remaining fingers. The result is either the twirling of a baton, as in the hand priority grasp, or the twirling of a mechanical gripper in the case of the object priority grasp.

Nguyen [52] develops the concept of a stable grasp by analyzing the simplified world of planar polygons constrained by multiple point contacts without friction. The fingers are modeled as virtual springs with controllable stiffnesses. His stability criteria are similar to those previously described: that the object is in static equilibrium and it may resist motions due to external forces (force closure grasps). These properties are embodied quite elegantly in the scalar potential function describing the strain energy of the virtual springs. The expressiveness and simplicity of this formulation has been noted by several investigators [36, 45, 48, 52]. The stability criteria above are satisfied if the potential function reaches a local minimum and if a motion in the vicinity of this minimum requires an increase in the potential. Nguyen's approach locates local minima by identifying positions where the gradient of the potential function vanishes and employs the Hessian matrix to describe the behavior of the potential in the vicinity of this minimum. The Hessian matrix allows Nguyen to demonstrate an actively compliant gripper, where we may specify both stiffness and the position of the center of compliance.

5. Towards a Manipulation Paradigm

The discussion presented thus far was intended to indicate the complexity of the human sensory mechanism which supports taction, grasping, manipulation and provides the only means of direct contact interaction with the environment as well as to point out the comparatively weak methods which have been used to model the behavior of this remarkably useful manipulator. In this section, we will attempt to focus on a subset of these considerations to determine the character a manipulator which functions adequately in the role of a dextrous end effector.

A structure for the control of a "prehensile" system is presented in Figure 5-1.

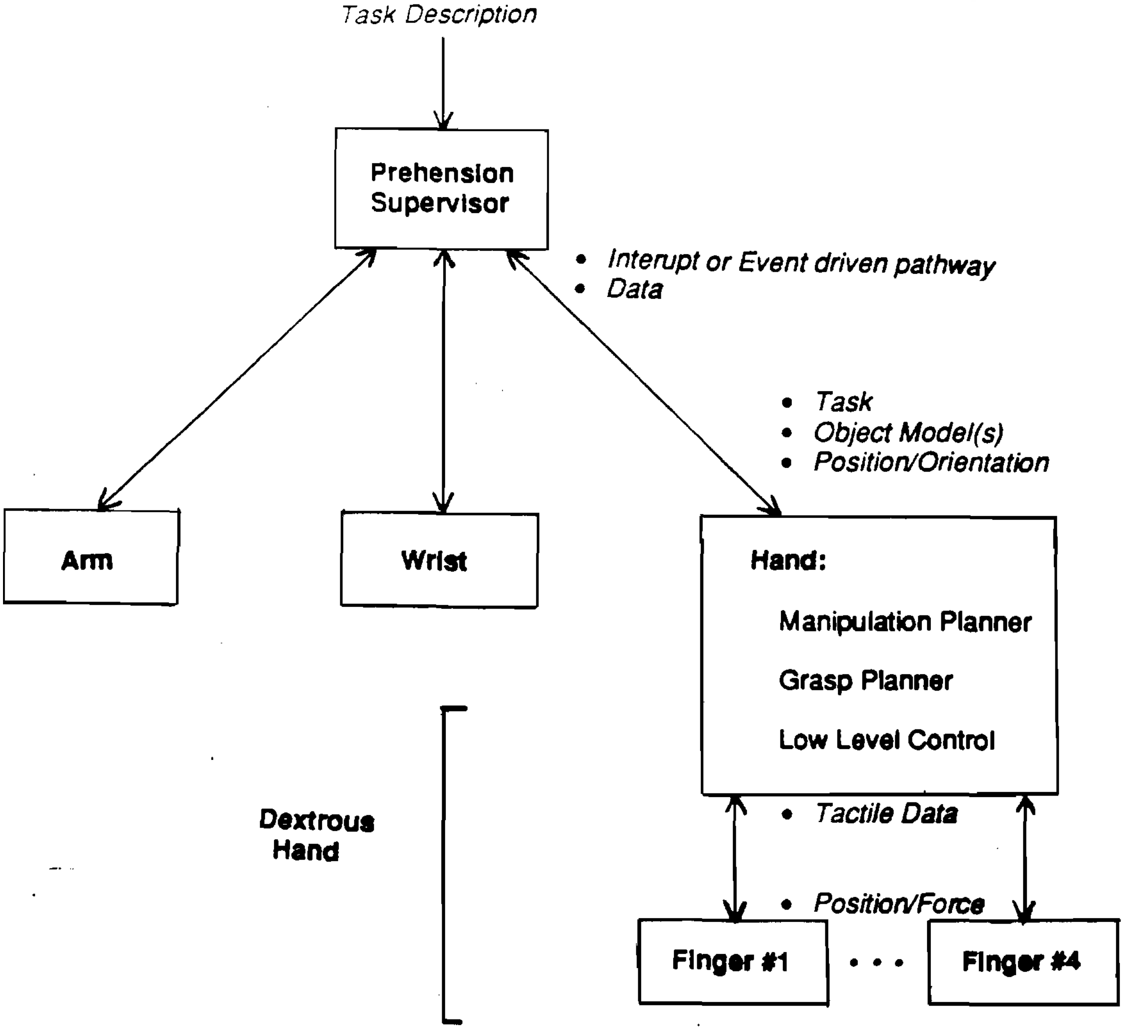


Figure 5-1: The Structure of a Prehensile System

The top-level of the proposed controller receives as its input, a description of the task. The prehensile supervisor then passes this information and other task specific information to the manipulation systems. We note at this point that the manipulation systems include those of the arm and wrist, but that we will limit our discussion to the hand alone. This approach allows the prehensile supervisor to operate in an essentially open loop mode, which permits the control of an object in the vicinity of the palm to be controlled locally. The distribution of the control here is somewhat similar to that in the human motor system. Recall from our discussion of the nervous system in humans, that the feedback pathways to the brain (the highest level supervisor in our model) are much too slow to permit classical feedback control of the extremities. The human nervous system distributes the control across the neural pathways themselves, specifically the spinal cord has been noted to short-circuit the feedback sensory information for the purpose of reacting to painful stimulus from the environment. The system for control presented here allows the same approach to be taken, the return pathways shown represent interupt or event driven pathways that implement reflex actions.

The "hand" shown in Figure 5-1 is the collection of hardware and software which (to some degree) allows the local control of the dextrous end effector. The mechanical component of the "hand" is reduced to four fingers for the sake of the discussion here, but the capabilities are fashioned after the Utah/MIT dextrous hand presented earlier in this paper. To this, we add the ability to efficiently acquire tactile information which will be used locally as well as passed upward in the control heirarchy. The low level controller indicated in Figure 5-1 allows Cartesian position/force control.

5.1. The Grasp Planner - Model Driven Finger Placement

Given a model of the object, a task and an absolute position of the physical object that is to be handled, we would like to be able to both determine the optimal grasp contact sites, and drive the fingers to their respective positions. The two principal independent variables in the selection of a grasp site are the geometry of the object and the particular task. The scope of the analysis must necessarily include the degrees of freedom associated with the wrist and arm, for example, an I-beam standing on its flange which is to be moved in a vertical direction might very well be grasped underneath the upper flange, but when presented to the system in a horizontal position, a quite different grasp is preferable followed by gross reorientations by the wrist and/or arm. The complexity of the problem suggests a controller which uses a vocabulary for speaking about the motion control of manipulators which is descriptive enough to apply to the general grasping problem yet is simple enough to allow the supervisor to synthesize task driven trajectories.

In this section, we examine how we might express the guidance of the fingers of a dextrous hand to grasp sites on the surface of an object. We will defer the discussion of how we might select the grasp contact sites until later.

Impe<dance Control

The problem is similar to the various manifestations of a generalized stiffness controller for robot arms. Neville Hogan has shown the utility of impedance control as it applies to a wide variety of control situations [30, 31, 32, 33, 34, 35, 36]. In particular, his approach to obstacle avoidance is found to be useful here. The thrust of his approach is to model the manipulation system, including both the manipulator and the object, as a complementary synthesis of admittances and impedances. The character of an admittance, when expressed in the terms of mechanical interaction, relates an input force to an output motion. A mass is then a mechanical admittance since it accelerates when an external force is applied. Likewise, the mechanical impedance reacts to an input motion to produce an output force which retards that motion. A spring is the obvious example of a mechanical impedance.

When the robot hand is modeled as an impedance, it is capable of dextrously supporting an object within a potential well described by the multiple contact impedances seen by the object. Moreover, when the manipulator is not in contact with the object, it can seek the most prominent local target potential. The latter eventuality is what we shall consider here.

During the initial phases of a grasp, the supervisor of the manipulator is presented with an object model, its position and orientation in the workspace, and a description of the task. As was mentioned earlier, both the object and the task will determine which positions in the workspace represent the optimal contact sites. The acquisition of the object requires both the selection of contact sites on the object and the generation of finger trajectories toward these positions. The framework of impedance control suggests that modeling all fingers as impedances and positioning appropriate local target potentials, we may simultaneously avoid tangling fingers and seek the contact positions determined by the supervisor.

The generation of paths for the fingers is equivalent to the assignment of appropriate potentials to the target and obstacle features in the manipulation space. As pointed out by Hogan, the impedances in the environment may be superimposed in regard to their effect on the environmental admittance even though some of them may be non-linear. Consider now the task of modulating the potential field in order to guide fingertips toward target grasp sites. A useful analog to the process is the guidance of a sticky marble along a deformable plane. The marble itself is represented as a repulsive potential so that marbles tend to repel each other, while the target position is the closest attractive potential to the marble. The term closest used here is somewhat vague, since the choice of which local minimum the marble will seek is a function of both the marbles position and velocity. But this simplification will not interfere with the discussion. In fact, the form of the potential function is not specified and may be modeled as a wide variety of well understood potential fields.

There are several forms that the impedance of the manipulator could take, most resulting from the intuition of the designer, or an analogous physical process. The most straight forward potential function is based on the strain energy of a deformed spring:

$$V_{spring}(r) = 1/2[k_x(x-xp)^2+k_y(y-yp)^2+k_z(z-zp)^2]$$

where the torsional terms have been neglected and is expressed by a relationship between an input motion and an output force of the form, $F=-kx$, for each dimension. Another commonly used impedance is the generalized damper, which is expressed by the input/output relation $F = -Bv$, where B is a damper strength and v is the velocity. The damper is not a conservative field; that is, the force on the object is not due solely to the position of the object, but is a function of the velocity. Note here that the damper produces an output force that is in opposition to the velocity and not simply directed along the axis between the object and the destination as it is in the case of the spring.

A repulsive potential function that is to be used in an impedance controller must vanish as the distance from its source grows in order to confine its effect to a local area. As suggested by Lyons [48], one candidate is:

$$V_{repulsive}(r) = -k_x\ln(x-xp)-k_y\ln(y-yp)-k_z\ln(z-zp),$$

the resulting force is inversely proportional to the city block distance from the source (xp,yp,zp) to any position (x,y,z) in the field.

These potential functions are limited in utility. The reason is that the resulting force on the object at some point in the field is directed along the axis between the potential source and the object. The controlability of this system is limited; it is useful to exert more of an influence on the trajectory of the object as it effects the angle of approach. To this end, a simple compound potential field is considered, which we will represent initially as the electric dipole.

The electric dipole [46] is modeled as two opposite point electrical charges separated by a distance, s, which is small relative to the distance, r, where the object is located. At position, P, a distance r from the midpoint of the dipole, the potential may be expressed (for $r^3 >> s^3$):

$$V_{dipole}(r) = [Qs/(4\pi\varepsilon_0 r^2)]\cos\theta .$$

Therefore, the potential due to a dipole falls off as $1/r^2$, and the force falls off as 1/r. The potential field and the lines of force for this type of field is illustrated in Figure 5-2.

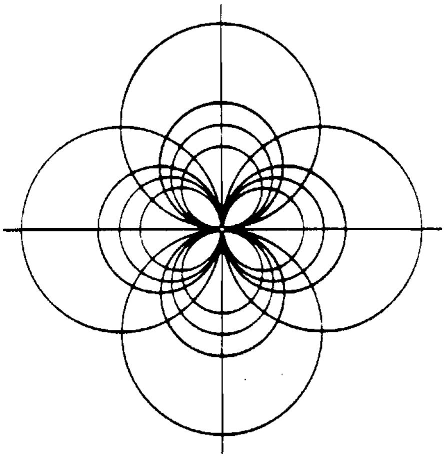


Figure 5-2: The Field due to an Electric Dipole

The distinguishing feature of this field is the existence of a preferred path or trajectory for a small positive (or negative) particle in the presence of this field. The lines of force represent the directions of the tangential accelerations experienced by the object. It is not difficult to extend this model of the potential field to the case where there are n-poles along an axis, or where there are continuous distributions of charge over surfaces.

Another physical interpretation of the potential fields described by the dipole is often utilized when analytical models of the laminar fluid flow are generated using potential flow gradients [66]. The physical system is similar to the electric dipole where the positive and negative poles are replaced by flow sources and sinks, respectively. The flow source is a hypothetical outward uniform fluid flow in all directions such that the velocity of the fluid at any point is the source strength over the total flow area.

$$V_{source}(r) = m/(4\pi r^2) = -d(\phi)/dr ;$$

where ϕ is the fluid flow potential, $\phi = m/(4\pi r)$. The flow sink is described similarly by simply reversing the sign of the above relation. The analog of the dipole from the fluid flow point of view is the doublet. The combination of a source of strength m at (a,0) and a sink of the same strength at (-a,0) produces a similar potential topology to that of the dipole:

$$\phi = (2am/r)\cos\theta,$$

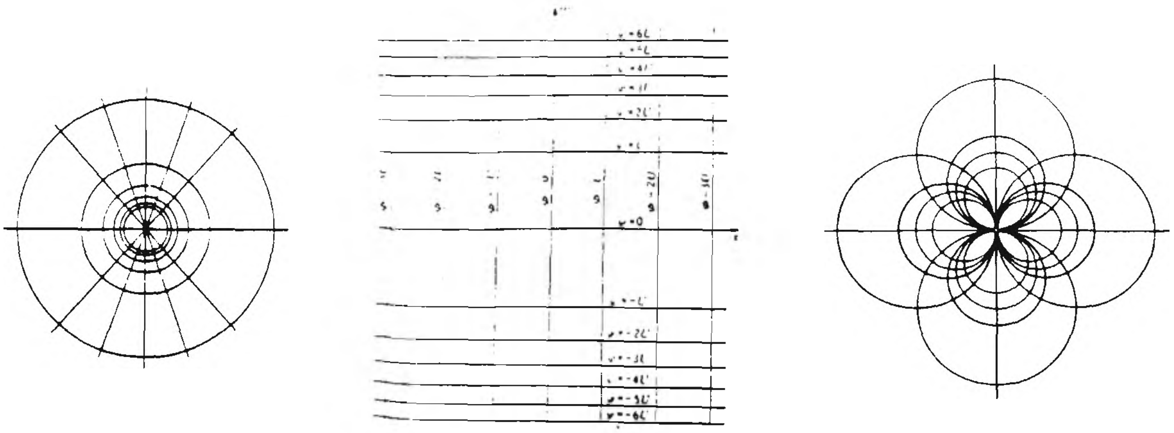
where (2am) is referred to as the strength of the doublet. This representation of the potential field suggests a model of the fingertip as a differential element of fluid mass which is drawn from source to sink along some streamline. The utility of this compound field is that in the absence of unexpected obstacles, the target position and the approach to the target can be controlled. The relative strength and the separation of the source and sink may be dynamically controlled to effect the trajectory of the fingertip. Moreover, the ideal (frictionless) fluid flow analogy suggests several useful compound fields which are simply combinations of idealized flow objects, such as: the sources and sinks we have already encountered, uniform flow fields, line sources and flows about an arbitrary angle. These trajectory primitives are illustrated in Figure 5-3. Figure 5-3 also includes the streamlines created by the various potential fields. The ideal fluid is frictionless (zero viscosity) so that there is no momentum exchange between streamlines. Under these conditions, the streamline represents the instantaneous velocity at every point along the path of a differential mass of an ideal fluid. The family of streamlines are described by a stream function (or stream surface). Since we are dealing with a frictionless fluid, the streamlines are everywhere perpendicular to the equipotential lines.

The control of a dextrous hand given this generalized impedance model of the environment is realized by placing a relatively low strength source at each fingertip, thus avoiding finger collisions, while simulating the object as a distributed set of sources and sinks and the goal contact sites as dominant sinks. Each finger may be controlled by a separate distribution of superimposed fields if necessary. If uncertainty is present and predictable, it may be used in a configuration space representation of the environment model where the dominant sinks representing contact positions are inside the object model. An illustration of the process as applied to two simple cases is presented in Figure 5-4. Other means of successfully handling uncertainty have been suggested by studies of insects [56], where failed contacts initiate rhythmic searching movements and potential contact points are tested by active excursions of the insects leg.

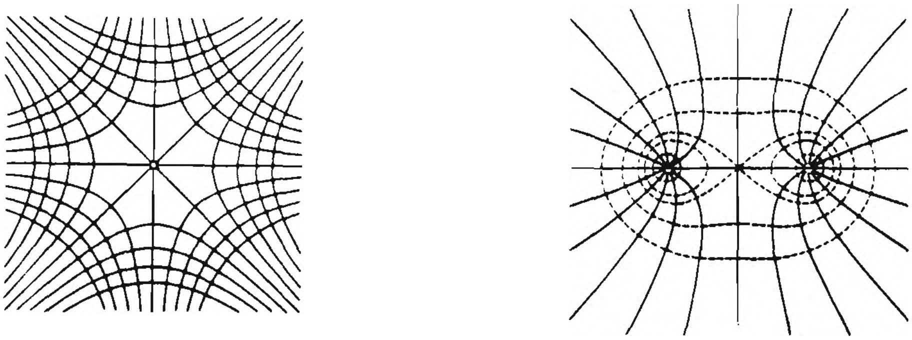
5.2. The Grasp Planner - The Role of Tactile Information

Model Registration

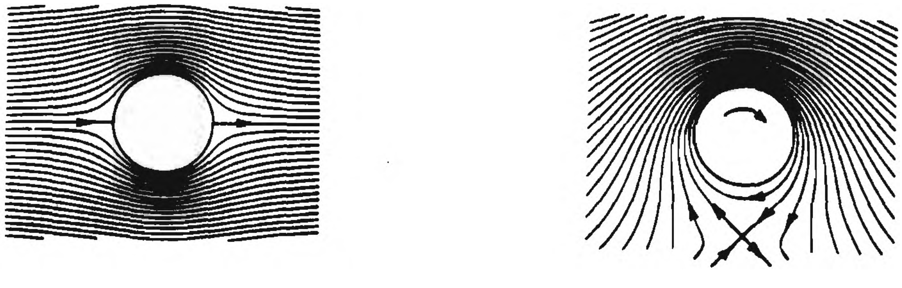
The tactile system presents many opportunities in the realm of object recognition and model registration since it provides an interactive means of acquiring three dimension information. The prehensile system with tactile feedback avoids the problems inherent in reconstructing three dimensional information from two dimensional visual images. Contact sensing allows knowledge driven data



a) source b) uniform flow field c) fluid doublet

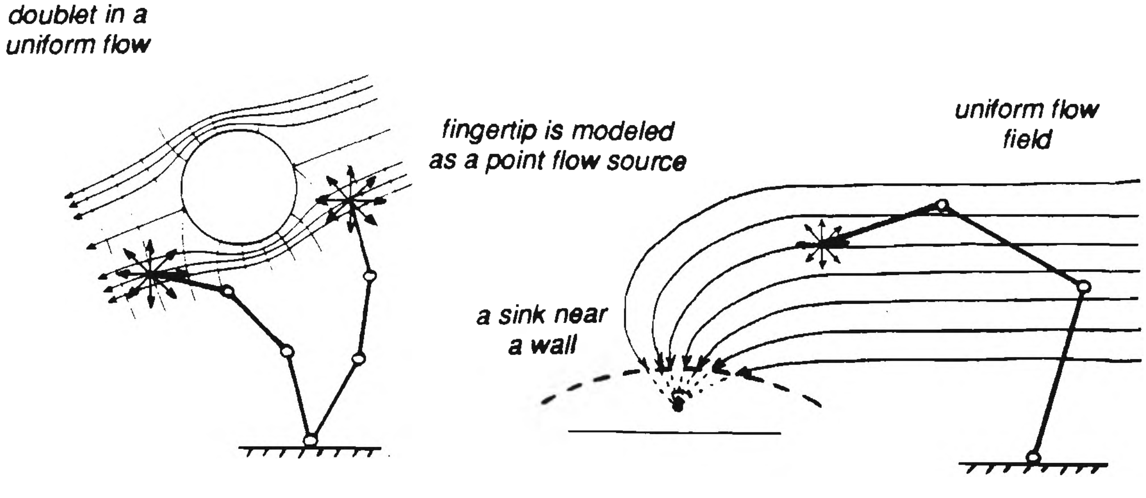


d) flow around a corner e) two sources or a source near a wall



f) uniform flow past a doublet g) uniform flow past a rotating doublet

Figure 5-3: Flow Field Primitives



a) Obstacle avoidance b) Target acquisition

Figure 5-4: Examples of Flow Field Trajectory Control

acquisition and thus avoids the torrential flood of information characteristic of most vision systems [2, 19, 20]. Moreover, the data returned is less prone to noise and error since the coordinates of the contact point can be determined as accurately as the joint positions of the manipulator can be measured and there are no problems with occlusion.

The character of contact sensing suggests that it may be extremely valuable in a work cell environment. Consider the problem of determining the location of the center of a sphere on a work surface. If we chose to scan the work surface with a laser ranging device, we would have to acquire a great deal of data and then look through it to locate a spherical surface. It is not uncommon, when scanning even relatively small areas with currently available ranging devices, to acquire data for several minutes. We may alternatively use a two dimensional imaging device, operating at video rates to direct a tactile search. In this particular case, the center of a sphere with a known radius can be suggested by a single contact position and surface normal. Moreover, with multiple contacts (a grasp), several parameters of interest might be measured, such as: mass, center of mass, connection to other shapes in the vicinity, material density, etc.

Tactile Guided Finger Placement in Manipulation

The problem of finger placement in the presence of uncertainty has already been posed. Another means of eliminating some degree of uncertainty is the acquisition of tactile data and the periodic re-registration of the object with its model. The stability of such a process is a function of the registration rate and serves to guide the commands of the Grasp Planner when gross finger movements are required.

Another implication of including tactile information in a potential field finger movement scheme is the incorporation of tactile landmark acquisition into the command motion. It is relatively easy to conceive of field streamlines which run along the surface of the object and induce contact with surface features. The gross finger movement can then be composed of event driven sub-sequences which require that some tactile feature be encountered before any subsequent movement command can be executed. If there exists a tactile feature such as an edge, we might wish to simply follow the feature to a new grasp site. It may therefore be valuable to couple the stiffnesses in a manner that facilitates the process of tactile edge following, or even more ambitiously, to allow an input force to a particular finger tip directed along a line or a plane, to instigate an active search excursion in some other plane. The same principle can be used to direct finger movement in the absence of tactile information if we couple deflections at one fingertip to movement of another fingertip. Consider a three fingertip grasp of an object where it is not possible to maintain a stable grasp if any of the fingers is removed. We may wish to reorient the object by sliding a finger across a surface (in the tangential direction). The deflections at the stationary fingers can be useful in directing the movement of the third finger in order to maintain a dynamically stable grip.

5.3. The Manipulation Planner - Dynamic Manipulation

Having developed a framework for describing an object in terms of idealized potential functions and to likewise define finger trajectories, it is now necessary to dynamically levitate objects within a reconfigurable potential cell. In the vernacular of impedance control, we would like to model the manipulator as a mechanical impedance which complements the admittance of the object. Consider once again the problem of controlling a sticky marble on a plane. The marble can be controllably restricted to a commanded point on the plane by simply tilting the plane. Similarly, the marble may be constrained in three space by translating and rotating the plane about the three coordinate axes. The plane modulation technique described here we will call *spatial modulation*. The control problem posed is substantially more stable if, in addition to spatial modulation, we actively control the elasticity of the plane. The marble is then suspended in an elastic hammock. The task before us then, is the description of a potential cell composed of multiple discrete contact points (two or more) which are distributed over the surface of an object model in the presence of uncertainty. Manipulation can then be composed of either spatial and impedance modulation, or the synthesis of and transfer to a new adjacent potential cell.

The idea of potential cell modulation is attractive from the perspective of the proposed Manipulation Planner if it provides a means of specifying a stable grasp which is both descriptive and simple to describe. A mechanical impedance representation of a 2-D hand is presented in Figure 5-5. Here, the hand is reduced to a fingertip contact which is coupled to the object through the viscoelastic element (spring/damper). The position and stiffness of the finger is controllable in a Cartesian coordinate frame. The contact modeled is non-linear, since it not only depends on the relative orientation of the finger, but for directions tangent to the object surface, it exhibits a threshold (proportional to the normal force) beyond which the object will slide with no further increase in the applied force. The viscoelastic elements represent the Cartesian stiffness or impedance of the finger. The model shown is realizable by the Utah/MIT dextrous hand where the the position, stiffness and damping of the finger, as well as the orientation of the distal phalange are controllable. A system similar to this was analyzed by Hemami *et al.* [28] which simulated the two-link planar biped system influenced by holonomic (connection) constraints. In particular, Hemami *et al.* develop the complementary nature of the viscoelastic elements in Figure 5-5 and the muscular actuation (control of the joint angles) such that the system exhibits asymptotic stability in the vicinity of an equilibrium operating point. The Liapunov stability of the system is considered to suggest methods of controlling the dynamic stability. In the case of a finger manipulating

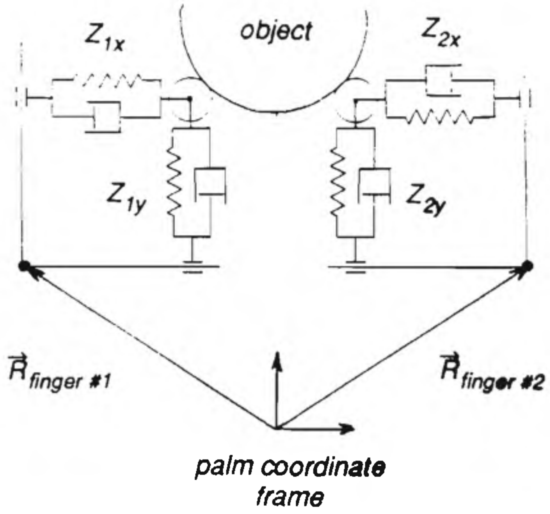


Figure 5-5: 2-D Impedance Representation of the Hand/Object System

an object, however, the relative angle of the finger and the object is not directly controllable as it is in the biped model. Instead, the relative angle between the object and the finger is dependent on the position and orientation of all the contact points and the object. Liapunov stability requires that should the potential function describing the coupled finger and object be positive definite, then the time derivative of the potential function must be negative semidefinite. Hemami *et al.* suggest the form of a Liapunov function which is positive definite (for suitable control inputs) while the derivative of this function is negative semidefinite. Therefore, the system can be stabilized provided that it is near a unique equilibrium operating point.

6. Summary and Conclusion

It has frequently been remarked by anthropologists that the human hand might very well have had a primary role in the success of the human being at competing with other biological species here on Earth. This truly general manipulation device allows us to interact quite well with the environment in which we find ourselves. In conjunction with our marvelously complex brains, the human hand provides a rich means of expression without which our success in this environment would undoubtedly have been compromised. This important observation has motivated many researchers to provide a similar capability to robots. The purpose of our paper is to motivate the development this capability.

The discussion begins with a description of the human biological hardware with which we are intimately (but perhaps not explicitly) acquainted. The results of this investigation may not map well into the engineering technology available to us, but serve to promote the understanding of the fundamental issues of general purpose manipulation. We examine both the mechanics of the human manipulator as well as its tactile/thermal sensing capabilities.

Following this cursory description of the human hand, we present a survey of technology developed to provide a similar capability. We review the accomplishments of investigators who have produced mechanical manipulators, tactile sensors and have integrated this hardware with control algorithms.

Finally, we attempt to look ahead to the challenges of future research. A description of stability provided by Liapunov is presented as it applies to the stabilization of biped systems. Alternatively, we might choose to describe stability as does Routh or Mathieau [43]. The purpose of the discussion concerning stability is the need to somehow specify kinematic or impedance control responses to object trajectories about an equilibrium point. If the manipulator is to respond to uncertain external force inputs, it must sense the trajectory of the object, evaluate its stability by some means and produce some compensatory reaction. Immediately, the prospects of extensive computation to establish stability (or lack of it) appear to be prohibitive. Perhaps it is most promising to envision a less computationally intensive, rule-based dextrous manipulator. This too presents a formidable challenge to the researcher. We are lacking the volumes of psychophysical observations which we have come to expect as, for example, in the field of machine vision.

The content of this paper hopefully provides a framework from which the insightful researcher may expand the boundaries of our understanding. It is clear that much more work is required, but seldom does the effort promise so great a return on our investment.

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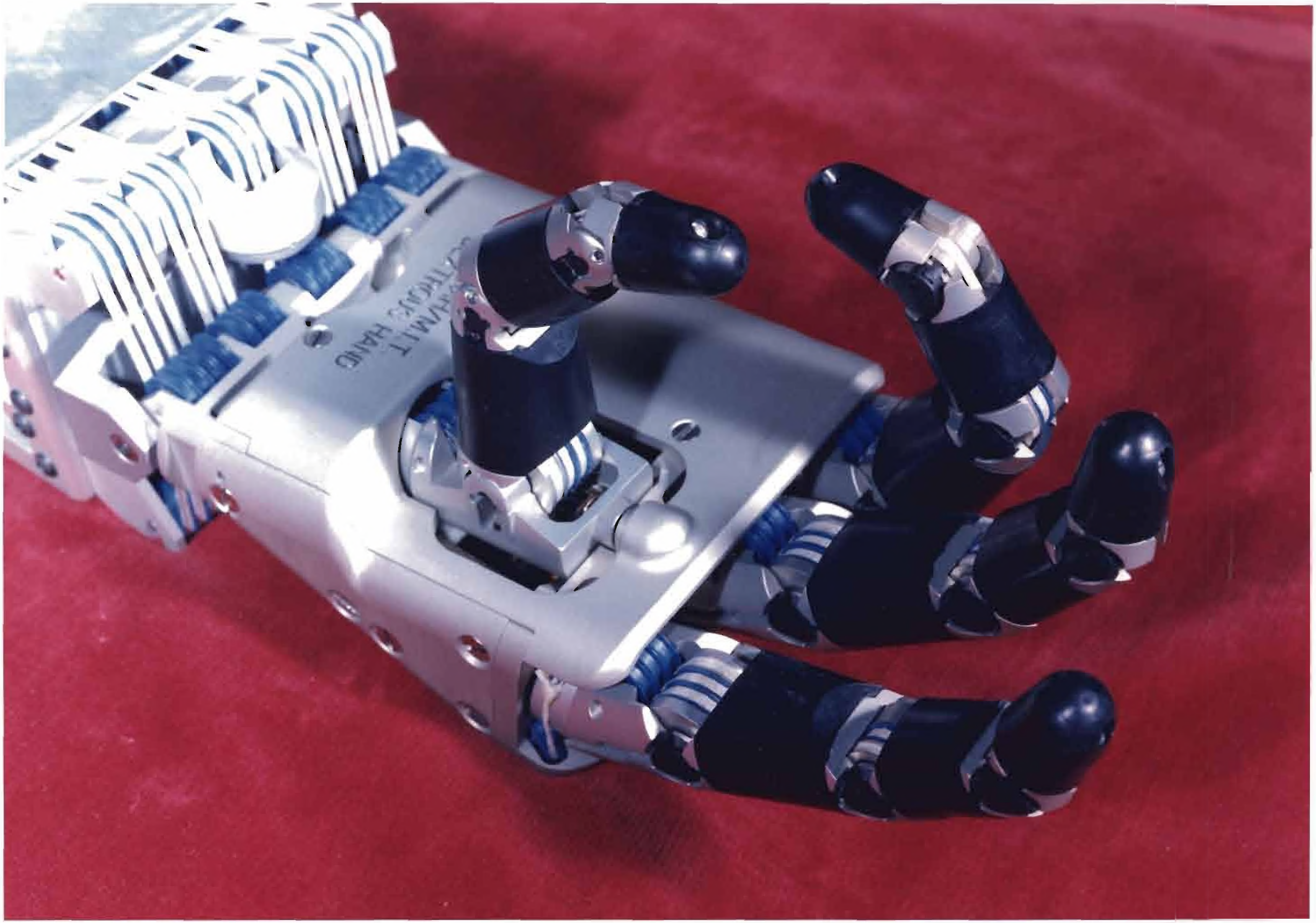

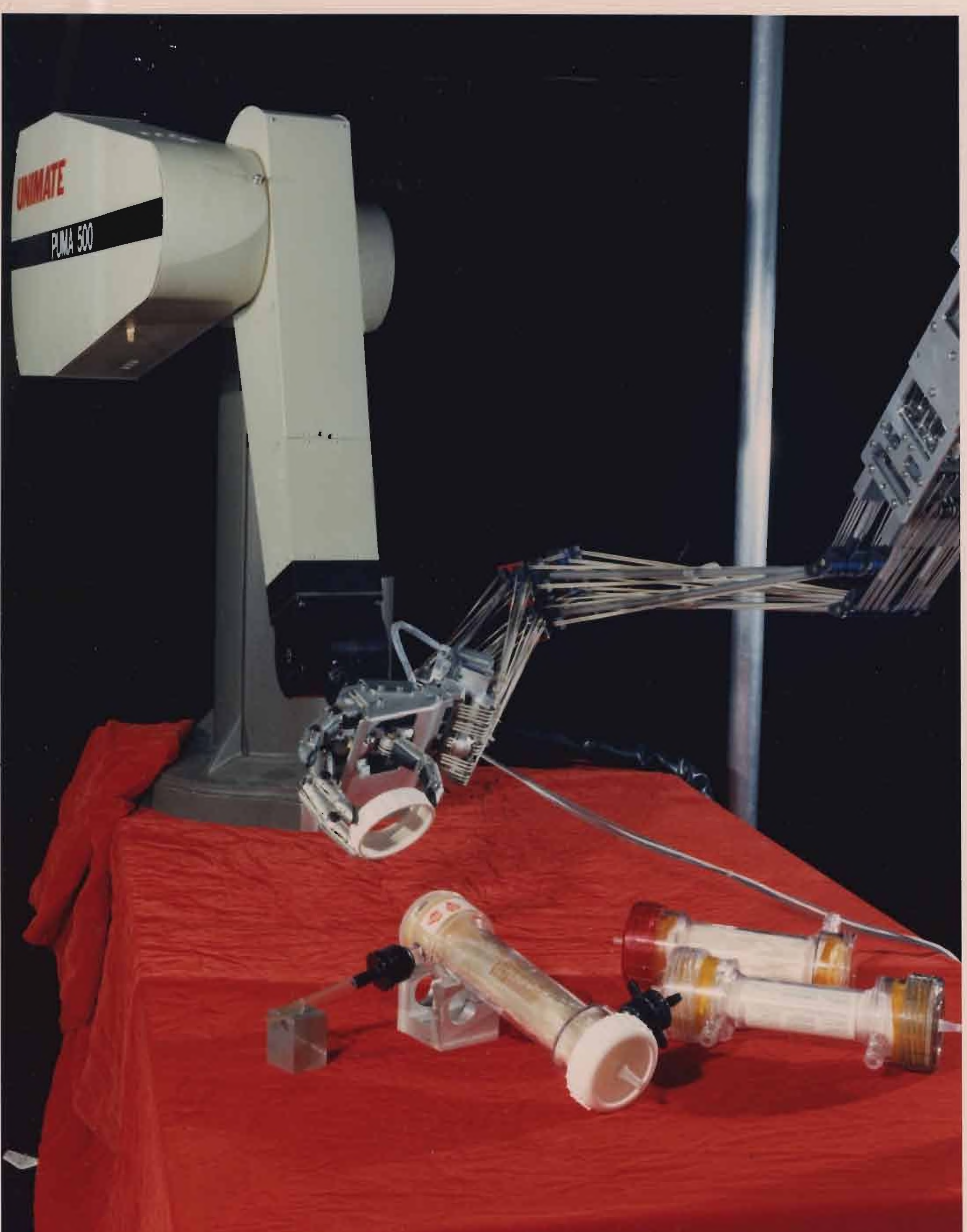
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