DESIGN OF THE UTAH/M.I.T. DEXTROUS HAND

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ABSTRACT

The Center for Engineering Design at the University of Utah, and the Artificial Intelligence Laboratory at the Massachusetts Institute of Technology have developed a robotic end effector intended to function as a general purpose research tool for the study of machine dexterity. The high performance, multi-fingered hand will provide two important capabilities. First, it will permit the experimental investigation of basic concepts in manipulation theory, control system design and tactile sensing. Second, it will expand understanding required for the future design of physical machinery and will serve as a "test bed" for the development of tactile sensing systems. The paper includes: 1) a discussion of issues important to the development of manipulation machines; 2) general comments regarding design of the Utah/M.I.T. Dextrous Hand; and, 3) a detailed discussion of specific subsystems of the hand.

INTRODUCTORY COMMENTS - MACHINES THAT PERFORM MANIPULATION FUNCTIONS

Expectations Are High

Judging by recent public interest, expectations are high that machines which execute complex manipulation functions will be a reality in the near future. This wave of optimism is encouraged by science fiction presentations depicting high performance robots; by the emergence of toys which move, interact and execute locomotion functions; and by certain industrial demonstrations of robotic manipulation systems which have been carefully orchestrated to convey images which imply that robots can do much more than is currently possible.

Apparent Markets Motivate Development Efforts

In addition to the general fascination which many people have for robots, the principal motivation for financial investment in the development of advanced manipulation machines arises from three commercial opportunities. First, it is believed that systems with machine dexterity can profitably perform a variety of tasks in the industrial sector; for example, assembly procedures, interactive inspection functions, etc. Second, it is obvious that such systems permit remote human presence in hostile or distant environments such as space and undersea. And, third, advanced manipulation machines could provide expanded capabilities for various military systems.

In all of the above areas the central objective is the replacement or augmentation of humans by robots which can execute manipulation tasks with: 1) greater economy; 2) higher performance; and, 3) reduced possibility of injury to people.

Progress Has Been Slower Than Expected

Unfortunately, the development of machine manipulation systems is emerging as a problem much more difficult than previously anticipated. General theories which permit the development of successful control systems and sensors haven't "fallen out" easily and the design and construction of machinery which can execute desired physical interactions has evolved slowly. A number of serious failures have occured both in the commercial sector and in the research and development community. Optimistic claims have aroused unrealistic expectations that progress would be rapid. Disagreements among participants in research projects have arisen as a result of failures and significant confusion now exists regarding how to proceed in the future.

It is becoming clear that progress has been slow for three basic reasons. First, the problems associated with the design and construction of machine-based manipulation systems are enormously difficult. It should be expected that some time will be required before issues are fully understood and demonstrable results are achieved. Second, although there has been much publicity regarding robot manipulation systems, intensive focus, in terms of effort and resources, has only been applied to this area for a short time. It is clear that significant resources will be required to achieve successful systems. Third, and unfortunately, work in this area has been undertaken with little comprehensive management and as a result balanced efforts have occurred in only rare circumstances. Future projects must be encouraged to evolve in a balanced way, with efforts expended simultaneously in both theoretical and applied areas. Major focus should be on understanding issues related to control systems, sensing systems, and in understanding how these complex machines can be made to function reliably.

Future Efforts Should Consider: Utility, Feasibility, Persistence, Balance, Experimentation and Demonstration

In order to provide a basis for understanding decisions made during the conduct of this work, as well as guiding future efforts to develop manipulation machines, a number of general issues should be reviewed.

Existence of a Market. In a long-term, general sense there can be little doubt of the utility (disregard cost for the moment) of devices which perform comprehensive manipulation tasks. Numerous examples exist where intelligent and dexterous machines could advantageously accomplish manufacturing functions, operate in hazardous environments, explore remote locations, provide changes in scale, function at high or low speeds, or accomplish other important functions. The economic opportunities which could be generated by such systems are indeed enormous.

Clearly, future systems must be practical, reliable and within cost guidelines. However, care must be taken to avoid excessively negative projections just because present research systems are awkward and disappointing. It should be remembered that economic success will be defined in terms of the achievement of specific and relatively limited goals, rather than generating those fanciful images seen in science fiction movies. In each situation the application and resulting expectations must be understood in terms of requirements for performance, reliability, and economy. Judgments should then be based on appropriate cost/benefit issues. Too many times a research tool is evaulated according to industrial standards or an industrial machine is considered inadequate based on research demands.

Evaluation of a system based purely on cost can also be a fuzzy process. In some applications it is permissible for a manipulation system to be quite expensive since its costs are dwarfed by the expenses of the overall program; for example, in outer space or undersea applications. In other cases, such as those in manufacturing environments, the cost of a manipulation system must be less. Finally, in the case of consumer products such as toys and home robots, the cost of individual systems must be extremely small.

Feasibility. There can be little doubt that manipulation processes can be accomplished by general purpose systems. Biology provides a stunning array of existense proofs which demonstrate that intricate manipulation is within the realm of possibility. It should be emphasized here, for those with certain presumptions, that the operation of biological machines is not based in magic. Nature produces systems which utilize real hardware that operates according to physical principles. Although it can be said that the basis for many biological functions is not yet well understood, it is undoubtedly true that, as research unfolds, many important and useful discoveries will be made in this area. Finally, the intent here is not to imply that the development of such systems will be an easy task, only that such systems can be developed.

Persistence. If machine-based manipulation systems have markets and are feasible in at least some forms, it is obvious that work should proceed with vigor in order to shorten the time before such valuable systems emerge. Of initial importance is establishing a clear and balanced understanding of the issues involved so that projects can be managed with emphasis on achievement of practical results.

Balance in Approach. The development process should be managed in order to identify goals which are realistic so that results can efficiently drive an expansion of the knowledge and technology base. Early activities should target achievable goals which expand understanding of basic issues related to: 1) task definition; 2) manipulation strategies; 3) grasping functions; 4) the use and integration of sensory information; and, 5) fundamental issues governing the design of machinery which will constitute these man-made manipulation systems.

Above all, the development process should emphasize an expansion of interdisciplinary collaboration by encouraging tolerance for multiple viewpoints and methods of approach. The ultimate goal should be understanding those principles which permit the design of successful systems. An example of current intolerance is the conflict which continually surfaces between those groups which follow traditional engineering approaches versus groups which include in their activities, the study of biological systems in order to gain insights into the manipulation process. The traditional and time-tested engineering approach is to construct a sequence of prototype machines which can be used to evaluate principles. Then, based on those principles, final systems are designed. A second approach, equally valid, but sometimes criticized, is the attempt to identify important principles through the study of biological systems. In the final analysis, both approaches, as well as other methodologies, can produce desirable results, and in all cases, information which could facilitate progress should never be ignored.

Demonstration. As always, there is a limit to the human capacity for pure visualization and conceptualization. At some point, physical machines must be constructed to: 1) provide a means by which concepts can be experimentally validated; 2) to provide indications as to the performance which will be required of physical machinery; and, 3) to permit judgments to be made regarding the value of a particular approach. Unfortunately, in the manipulation area there has been a significant lack of experimentation due primarily, not to conscious avoidance, but to the unavailability of suitable research equipment.

The Utah/M.I.T. Dextrous Hand - A High Performance Research Tool for the Study of Machine Dexterity

Just as research is conducted in a number of areas using reliable, flexible, general purpose computation systems, so work in the machine manipulation area should be conducted with well developed manipulation systems which can be used as "test beds" to explore concepts related to both manipulation theory and machine design. The existence of such tools can simplify research activities and allow investigators to proceed toward understanding issues and concepts rather than being continually sidetracked by problems with experimental devices.

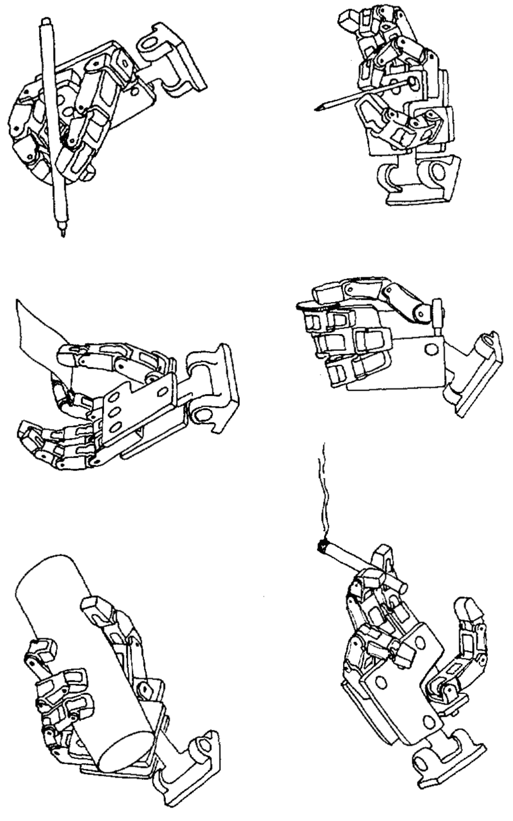

Figure 1. Originally proposed configuration for the Utah/M.I.T. Dextrous Hand. Reprinted from Reference 1.

It was therefore decided that an effort would be undertaken to develop a research tool with: 1) many degrees of freedom; 2) very high active and passive performance; 3) acceptable reliability; 4) the capability to serve as a vehicle for studying a broad variety of tactile sensing systems; and, 5) via modularity, the possibility of geometric reconfiguration in order to address evolving experimental objectives. In 1982 the Utah/M.I.T. Dextrous Hand Project began with its objective being the development of the hand which is schematically illustrated in Figure 1. Since that time final Version III system has been produced as shown in Figure 2. The following sections describe the Dextrous Hand and review a number of general issues important to the design of such systems.

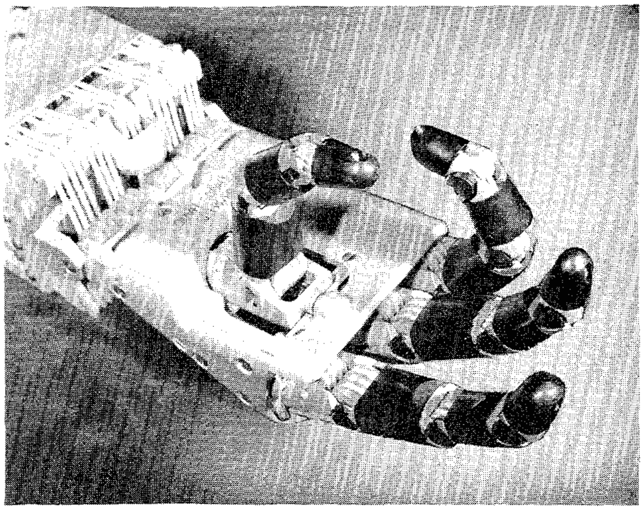

Figure 2A. Photograph of the Version III Dextrous Hand.

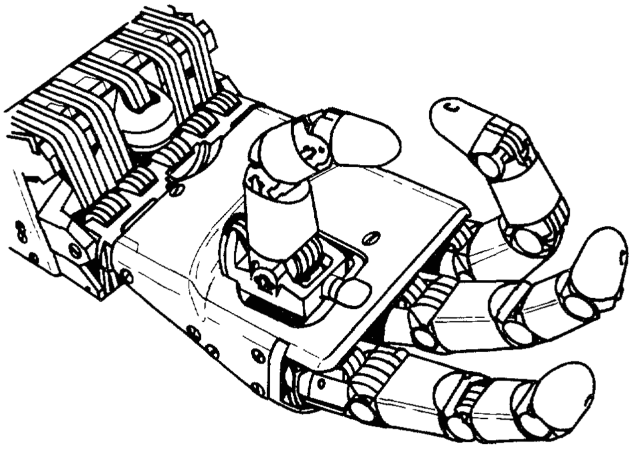

Figure 2B. Line drawing of the photograph shown in Figure 2A.

GENERAL COMMENTS REGARDING DESIGN OF THE UTAH/M.I.T. DEXTROUS HAND

Goals of the Project

The primary objective of the project has been the design and construction of a general purpose research tool for the study of machine-based manipulation. From the outset, the emphasis has been on producing a system with extraordinary performance (both active and passive), and as such, factors related to cost, power consumption and other practical considerations have been de-emphasized. The device is not intended for near-term application in an industrial environment, but as a research tool with sufficient functional richness to permit a broad variety of experiments to be conducted, aimed at understanding fundamental concepts and machine design issues. Goals can be reviewed in greater detail by addressing specific performance issues such as: 1) speed; 2) strength; 3) range of motion; 4) the capability for graceful behavior; 5) reliability; 6) the possibility of reconfiguration; and, 7) cost.

Speed. The speed of the digits of the Hand have been designed in anticipation of performing dynamic manipulation tasks. This requires that the fingers be capable of interacting with objects which might fall or move rapidly under the influence of gravity. Such motions require that fingers execute rapid motions with frequency components which exceed 10 Hz. At these frequencies the digits should move in such a manner that manipulated objects are not damaged by rapid finger contact. This requires that actuated masses be low so that high speed contacts produce minimal impact. Furthermore, the actuation system should be capable of tolerating large accelerations imposed by interactions with moving objects.

Strength. Since the Hand must interact with objects of "hand size," and considering that such objects will have densities ranging from Styrofoam to metals, and that lubricated surfaces will exhibit relatively low coefficients of friction, strength of the DH has been addressed with considerable emphasis. The present system is capable of producing tip forces of 7 pounds which permit very positive fixation of objects, especially when multiple fingers operate in a coordinated fashion. Even though strength of the DH is acceptable, a current objective is to identify ways to triple the strength of the hand while maintaining its speed capabilities.

Graceful Behavior. Gracefulness is a quality which can be observed in natural systems of many types. It is probably true that graceful behavior is not a feature added for aesthetic appeal, but that grace is generally a byproduct of a system operating with low internal loadings on structures, and without excessive internal antagonisms which lead to inefficient operation. In other words, grace and efficiency appear to go together. The Utah/M.I.T. Hand is quite graceful in operation and this quality is primarily a result of the impedance characteristics of the pneumatic actuators. The actuators have been designed to exhibit low stiffness, low stiction, and the mass of actuated elements is low since only the tendons, pulleys and graphite pistons actually move to operate finger joints. These factors lead to a very distinctive "feel" when the DH is externally manipulated. In fact, the individual digits can be externally driven up to very high frequencies without damaging internal components.

It should also be noted here that, although compliant operation of the system is advantageous in many ways, it also presents problems for the control system. Soft systems tend to destabilize if high loop gains are used to achieve positional accuracy. It could be said here, loosely speaking, that during free motions of a manipulator, grace is a result of the "smart throwing" of segments. It is interesting that the capability to be thrown depends or their being capable of mantaining low impedance even at high speeds. Also, being thrown through space to some future rendezvous requires knowledge of the system and its task. Thus, in the case of the DH, the control system must include greater complexity in order to govern the behavior of compliant fingers involved in activities requiring rapid and precise coordination.

Reliability. The Utah/M.I.T. Dextrous Hand was not designed as a laboratory trinket for short-term investigation of some local principle. The system was designed to be a functional, reliable machine aimed at long-term operation. Subelements have been exhaustively evaluated and the design continually reviewed in order to provide information necessary to enhance the performance and reliability of future systems. Of course, subsystem reliability will become an increasingly important issue as this DH and other similar machines evolve to greater levels of complexity.

The Possibility of Reconfiguration. The Dextrous Hand was designed as a series of modules which can be interchanged for maintenance purposes, and also to permit reconfiguration of the system into alternate geometries. Even though all four digits are essentially identical, outer surfaces can be modified and base mountings repositioned in order to alter finger shape and grasp geometry. Since the system is tendon driven, the 32 actuation systems can be used in end effectors of almost any configuration by simply rerouting tendons. The low level primary control system shown in Figure 17 is also flexible in that it can, via inputs from the higher control system, execute system servo functions with dynamically varying loop gains according to the specific requirements of the end effector and its task.

Cost. Since the initial system is intended to be a research tool manufactured in small quantities, cost has been a secondary consideration. Nevertheless, system modules have been designed to permit low cost if manufactured in significant numbers. It is intended that, subsequent to a period of research, simplified versions of the Utah/M.I.T. Dextrous Hand will be produced for industrial application using less expensive modules evolved from the original system.

On the Choice of Anthropomorphic Geometry

At the beginning of the project a search was made for previous work which would indicate the most desirable configuration for a research oriented robotic end effector. A number of papers were found which reviewed the subject under a rather restricted set of assumptions which related to: 1) the number of actuated elements (fingers) and the geometry of their contact with manipulated objects; 2) the quality of contact between fingers and objects (frictional characteristics); 3) the geometric complexity of the manipulated object (planar versus three dimensional objects); 4) the type of sensory information available to the central controller (joint torques, touch information, etc.) and other issues. The analyses included only simple types of static grasp using fingers with localized contact points and no real consideration of the palm as a valuable platform against which fingers can position objects. Furthermore, papers included no discussion of hand geometry and its influence on higher control issues such as those relating to task, manipulation strategy and grasping functions. Previous work was, due to the complexity of the problem, quite inconclusive in the sense that no clear direction was inferred regarding end effector configuration.

It was therefore decided to attempt an anthropomorphic geometry for the following three reasons. First, the human hand is an existence proof that a wide variety of very complicated, manipulative tasks can be accomplished by a single system provided that the end effector includes sufficient complexity to address proposed tasks and that the control system and its sensors are adequate. It was considered that, if a dexterous hand were developed with performance capabilities similar to the natural hand, that research could progress with a primary emphasis on control and sensing issues without being hampered by marginal performance of end effector machinery. Secondly, it appears that, from an experimental standpoint, an anthropomorphic configuration is desirable since it allows the human researcher to compare operations of the robot hand with operations of his own natural hand. It seems clear that, in a situation where almost nothing is really known regarding ideal configuration versus task objectives, the advantage of beginning with a system similar to the researcher's hand is unassailable. Thirdly, an anthropomorphic configuration has potential application as a slave element in a teleoperation system. In fact, a master system has been developed and the Utah/M.I.T. Dextrous Hand has been used successfully as a research device aimed at understanding issues which influence the performance of remote manipulation systems.

Unfortunately, it was not actually possible to achieve an exact anthropomorphic configuration as a result of packaging problems relating primarily to tendon routing. The final, quasi-anthropomorphic geometry, is as shown in Figure 3. The Figure illustrates the spatial positioning of the joints and the orientation of their axes.

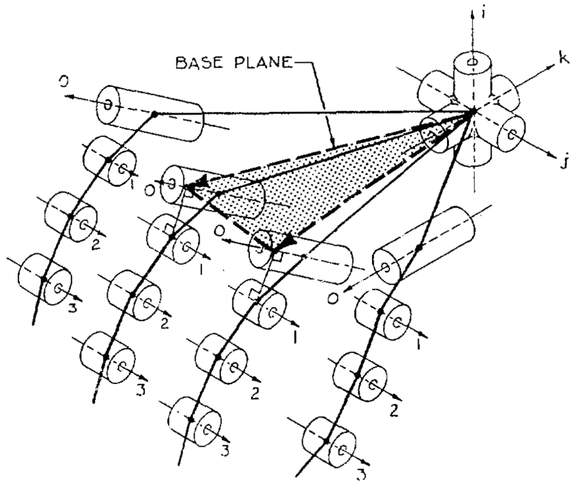

Figure 3. Configuration of the Dextrous Hand. The orientation of the axes of each joint are shown. Note that in the Version III hand, the 0 joints of the fingers are parallel to the base plane.

Specific deviations from anthropomorphic geometry include the following. First, the hand contains only three fingers and one thumb. The fourth, or "little finger," was eliminated to avoid complexity since the necessity of that finger could not be immediately shown. Second, the first two joints of each digit (the 0 and 1 joints as shown in Figure 3) were necessarily separated in order to allow tendons to be routed in a manner which would result in reliable operation. Note that for reasons of strength and fatique life, flat belt tendons were selected and that routing such flat elements must be accomplished via a sequence of planar bends separated by axial twists (see Figure 4). If the joint included two intersecting axes, certain regions of the tendon would be subjected to undesirable two dimensional deformations.

Third, the axis of the most proximal joint (the 0 joint) lies parallel to the base plane rather than tilted at 30 degrees as shown in Figure 3. Note that, in the natural joint, the 0 joint is essentially perpendicular to the base plane. Motivation for this change again relates primarily to tendon routing limitations. This alternative should not be considered negatively however, since it allows the fingers to achieve significant side-to-side excursions (0 joint mobility) when the 1 joint is flexed to the 90 degree position. These 0 joint motions actually improve mobility of fingertips when they oppose the thumb in contrast to the situation found in the natural hand where 0 joint mobility is almost null when the 1 joints are flexed to 90 degrees. Fourth, due to tendon routing difficulties, the base of the thumb was placed in the palmer section between the first and second fingers. This allowed tendons to be routed over the wrist and through the palm to the thumb in a reliable manner. Although, in a nonanthropomorphic configuration, the thumb does maintain sufficient 0 joint mobility to interact with all fingertips in a near natural manner. The existing configuration has been successfully operated in a teleoperation mode with suitable transformations made between motions of the master unit and finger positions of the DH. Fifth, and again because of tendon routing problems, the wrist joint is larger than desired. The enlargement, which causes some appearance problems, in fact provides additional space for the placement of 32 tendon tension sensors whose output is used for management of actuation systems and estimation of individual joint torques.

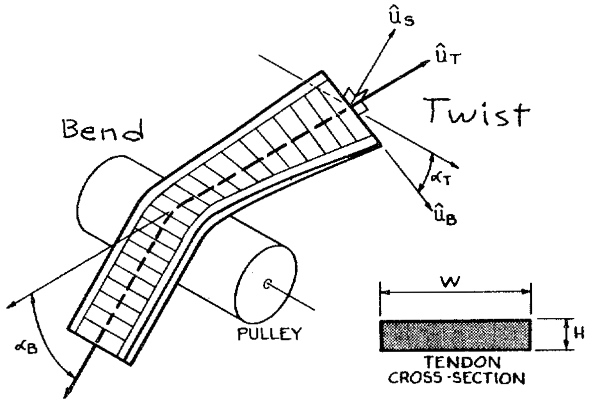

Figure 4. Tendons are routed throughout the system via a series of axial twists and bends over pulleys.

Comments Regarding Design of System Elements (DH)

From the outset our objective was to use the most advanced, yet practical technology so that performance could be maximized while achieving an acceptable level of reliability. The most important guiding principle used to manage the project has been the maintenance of balance. That is, understanding that design involves the simultaneous satisfaction of multiple conflicting objectives and that no specific area can be overemphasized at the expense of another. General success requires individual successes in all subareas, both conceptual and those relating to machine design. Efforts have included simultaneous work in eight areas of system design including: 1) structures; 2) internal sensors; 3) external sensors; 4) actuation systems; 5) remotizing systems; 6) covers; 7) communication networks; and, 8) computation systems.

Efforts have also focused on understanding the requirements for lower level control systems which provide system management functions. Essentially, the lower control system is responsible for producing a system which "does what it's told" with speed, strength and stability. Mid and higher control systems are now being investigated since the DH is now available for experimental activities.

In the design of all subsystems, simplicity has been a major objective. Every attempt has been made to eliminate unnecessary components and to design various system elements to be free from the need for continual calibration and maintenance. Closely associated with the avoidance of complexity has been the avoidance of precision. In all subsystems, close tolerances and the possibility of interfering components has been avoided.

In order to simplify control requirements actuator elements have been designed to exhibit desirable qualities as a result of intrinsic characteristics, rather than via attempts to modify actuator performance through the use of compensating feedback loops. In fact, the principle reason for the excellent passive performance of the DH is the intrinsic qualities of the pneumatic actuators. Finally, as previously mentioned, the DH was built in a modular fashion with a minimal number of different subsystems so that intensive efforts could be focused on understanding the behavior of a fewer number of elements rather than dealing with many different components.

Relocation of Actuators Outside the Hand. Of course the most desirable configuration for an anthropomorphic robotic hand is as shown in Figure 5. In this case all structures, actuators, sensors and covers are an integral part of one system with only simple connectors emerging for power, input commands, and to output sensor information. Unfortunately, a number of realities totally preclude such a possibility if the system is to include reasonable performance goals in relation to strength, speed, reliability, etc. The difficulty of generating a totally self-contained hand is demonstrated by natural systems which also require remotization of major muscles to the forearm area proximal to the hand.

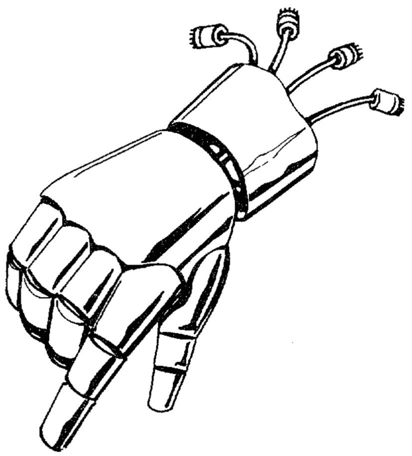

Figure 5. An ideal configuration for an anthropomorphic, dexterous, robotic hand.

The first retreat from the totally self-contained alternative was the relocation of actuators outside of DH to some convenient location. The relocation allows more volume within the DH to be used by structures, joints and sensors. This compromise also permits greater design flexibility for the actuators since they can be larger, with an emphasis on performance rather than restrictions in size, shape, weight and volume. Obviously, remotization of actuators also provides an opportunity for cost reduction.

The Use of Tendons. 'With the decision to remotize actuators, various methods for the transmission of mechanical energy from actuators to the hand were explored including hydraulic and pneumatic systems, mechanical linkages and flexible tensile tendons. Various trade-offs were exhaustively reviewed and the tendon approach was finally selected. Tendons provide a number of advantages including very low mass, and the possibility for stiff transmission of energy over complex pathways. Tendons require no bulky terminal energy transformation systems such as cylinders used in hydraulic systems and motors with transmissions used in electrical systems. It is also important to note that tendons possess an additional advantage in that their routes can be designed to augment the loading of structures as well as imposing intrinsic coupling between the motions of joints (i.e., tendonesis).

Originally it was intended that high strength polymeric tendons be developed which were suitable to operate in lubricated and flexible channels similar to biological systems and to the Bowden type brake cables found in bicycles and motorcycles. Unfortunately, after exhaustive work with various tendon structures, with wet and dry lubricants, and with assorted bearing surfaces, the lubricated-channel alternative had to be disregarded in favor of pulley-based systems. Pulleys appear to be the only method which allows for both high strength and low friction operation. Pulleys unfortunately include problems with complexity and reliability, and they consume significant volumes within the DH, especially in critical regions surrounding joints.

In order that each joint could be individually controlled, subject to a minimal number of additional constraints, it was decided that two tendons would be routed over each of "n" joints (the "2n" versus the "n+1" configuration). Although this approach consumes additional volume and imposes higher levels of complexity within the DH, it was determined that the "2n" configuration was the more conservative approach and that since the system was to be a research tool, maximum levels of flexibility in operation should be maintained. If, however, it is determined at a later point that a lower number of tendons can be successfully utilized, that approach will be pursued.

It should be noted here that tendons have not been as much a problem with reliability as previously anticipated. The current tendon configuration, during conservative life tests as described in Reference 1, performed over 6 million cycles. It is our goal, with continued work, to achieve a life of 50 million cycles under the same experimental conditions.

Motivation for the Remotizing System. It was intended that, during initial experimental phases, the DH would be positioned in space by a manipulator arm configured such as shown in Figure 6. Due to the limited lifting capabilities of existing robots it was unlikely that the entire Dextrous Hand and its actuation package could be accurately and quickly moved around in space, so it was decided to construct a remotizing system to conduct tendons from the actuation package, which remains in a static position, to the DH, which is oriented by the robot arm. The remotizing system shown in Figure 6 includes 32 tendon pathways in four subsystems, each of which include series of longitudinal beams and rolling joints. The longitudinal beams support the compresive stresses imposed by tendons and the system of rolling joints permit motion of the remotizer without altering tendon path lengths. This configuration includes the side benefit that no torques are imposed on the remotizer joints as tendon tensions are varied. The remotizer is then a very passive system which allows the DH to be freely positioned in space while receiving substantial energy from the actuation package. The present configuration allows the DH to be positioned everywhere within a cube with three foot sides.

Selection of the Actuation System. The selection of the actuation approach was a difficult procedure since severe constraints exist with respect to both performance and configuration. Actuators must exhibit extraordinary performance under active control where the DH is primarily driven by commands from the central control system. The actuators must also attain performance of a different kind when passively manipulated by external loads such as those produced when the hand interacts with objects. Also important are factors relating to weight, size and geometry of individual actuators, especially considering that 32 individual actuators are required to operate the DH.

A number of alternative systems based on hydraulics, electrics and pneumatics were investigated. Unfortunately, when comprehensive sets of constraints were applied in the selection process, no commercial systems were found to be suitable for use. After a series of fundamental studies, simulations and experimental procedures, the pneumatic approach was selected for implementation. It should be emphasized here that the pneumatic approach was not selected because it represents the "easy" approach. The development of the present electro-pneumatic actuator was a complex process spanning three years, a number of complex computer simulations (up to 22nd order system models), four stages of prototyping, exhaustive experimentation and the development of a high performance, low level control system for supervision of the DH and its actuator package.

The selection of the pneumatic approach was not based on a single quantitative analysis, but: 1) a series of general performance requirements formulated during previous work; and, 2) broad knowledge of the characteristics of various real, physical systems. Attitudes regarding performance are very briefly reviewed in the following two comments:

Active Performance. Active performance relates to the operation of the Dextrous Hand in response to commands from the central controller. Since it is intended that the DH have strength approximately equivalent to the natural hand, the actuators were targeted to produce forces of 50 pounds. (The existing system actually generates only 25 pounds.) Since the DH is intended to engage in real time manipulation of objects of approximately hand size it was shown that the finger should operate at frequencies exceeding 10 Hz. In order to maintain acceptable positional accuracies during free space operation of the hand it was concluded that positional stiffnesses of the finger tip should be at least three pounds per inch without destabilizing finger operation.

Passive Performance. Developing a system with suitable passive performance has probably been the most difficult aspect of the project. Passive performance is the least well understood issue and requires the design of systems which emphasize subtlety and delicate behavior rather than brute strength. Simply put, our goal was the development of actuators which could maintain very low intrinsic output impedance at substantial frequencies (for example, above 25 Hz). To address this goal, the possibility of using pneumatic cyclinders was explored since such systems can possess very low actuated mass (piston masses) while being capable of producing large forces. The compressability of the gas adds an intrinsic compliance to the system which functions at speeds in excess of those achievable via an active feedback system for behavior modification. The pneumatic cylinder approach however exhibits a primary disadvantage if the cylinder is driven by a flow control valve. With a fixed flow, the compressability of the gas allows the piston to act as a spring which oscillates against the masses of the finger. This produces a system with low damping and, because of delays, a high tendency towards unstable oscillation.

It was therefore decided to develop a pneumatic valve with an integrated pressure control loop so that the driven pneumatic cylinder would operate as a force source thereby avoiding oscillation problems induced by gas compressability or by the compliance in remotizing structures and tendons. The development of a pressure control valve was a complex undertaking since the valve must possess speed and flow capacities sufficient to dominate system operation at frequencies exceeding cylinder resonant frequencies (i.e., whistle frequencies).

Ultimately the two stage jet pipe system shown in Figure 13 was selected. As shown in Figure 12 each joint is operated by two antagonist actuators which are controlled to produce desired output torques and cocontraction levels as further discussed in References 1, 3 and 4. The use of the actuators as antagonist pairs results in a very high bandwidth, low output impedance system which enables the fingers to easily interact with objects under force control with no tendency towards instability. When the system operates without contact in free space, instabilities occur if joint stiffnesses are adjusted above certain levels. In order to extend the level of stiffness achievable during noncontact motions, dampers were added to each actuator as shown in Figure 12. Also, as discussed in Reference 1, stiffness can be automatically increased upon contact with objects as indicated by tactile sensors (proximal stiffening). (Note that without dampers the actuation package is capable of operating the finger's number 3 joint at frequencies in excess of 60 Hz). The resulting system is an excellent compromise which permits free operation at speeds up to 10 Hz while simultaneously allowing for high compliance interactions with solid objects. If desired, actuator performance can be further enhanced by expanding controller function based on information from tendon tension sensors in the DH.

Joint Angle Sensing Systems. In order to obtain accurate joint angle information for control purposes, it was decided that the sensors be located at the joints within the fingers themselves. An alternate choice would be to monitor tendon deflections at the actuators and determine joint angles by back computation. This approach would be subject to excessive errors and would drift should lengths of tendons vary or their terminations slip. A number of alternative methods for angle sensing were investigated including potentiometric, capacitive, optical and magnetic. Potentiometric alternatives seemed straightforward, but introduced problems with packaging, susceptability to intrusion by contaminants and reliability. Optical and capacitive systems, based on discrete measurement techniques, were complex, had limited resolution, were fragile and could be unreliable in certain circumstances. Also, due to their digital nature, the acquisition of angular velocity information introduced significant computational time delays which are undesirable if such information is to be used within servo loops. Finally, a magnetic approach using Hall effect sensors was explored and has proven to be very desirable. This system is reliable, proportional, and compact. System elements are totally encapsulated so that intrusion of dirt and other contaminants is not possible. Noise levels produced by the system are low and signals are smooth enough for direct differentiation to provide velocity information. The present system exhibits one disadvantage in that operation in the presence of strong magnetic fields can produce errors. Consequently, present efforts are aimed at a dual Hall effect system which configures transistors in a bridge in order to desensitize the system to external magnetic fields.

Tendon Tension Sensors. For a number of reasons it appeared important that tendon tensions be monitored in order to provide information regarding the torque imposed on individual joints as well as the possibility of providing information to the controller for actuator compensation. Ideally, tendon tension sensors would be installed distally at the insertion of tendons at each joint and proximally at the output of each actuator. Such a dual system could provide valuable information for the compensation of elastic and frictional characteristics of the tendons. However, due to packaging problems and issues related to complexity, a compromise system was selected. As shown in Figures 6, 7 and 10, 32 tendon tension sensors are located in the wrist. Each sensor uses a semiconductor strain gauge bridge to monitor beam deflection which is proportional to tendon tension.

DESCRIPTION OF THE UTAH/M.I.T. DEXTROUS HAND (DH)

Specific Subsystems of the DH

Systems for Spatially Positioning the Hand. Figure 6A is a photograph depicting a typical experimental configuration for the DH. Figure 6B is a line drawing included to indicate system subelements. The Dextrous Hand (A) is holding an object for assembly. The Hand connects to the wrist (B), which attaches to the remotizer (C). The remotizer carries tendons from the actuator package (D) which is maintained in a static position by an external mounting. The hand is oriented in space by a PUMA robot (F). To generate additional experimental flexibility components in the manipulation field can be oriented with respect to the hand assembly by a powered, moving table (E). Degrees of freedom of the table are: translation X, translation Y and rotation θ.

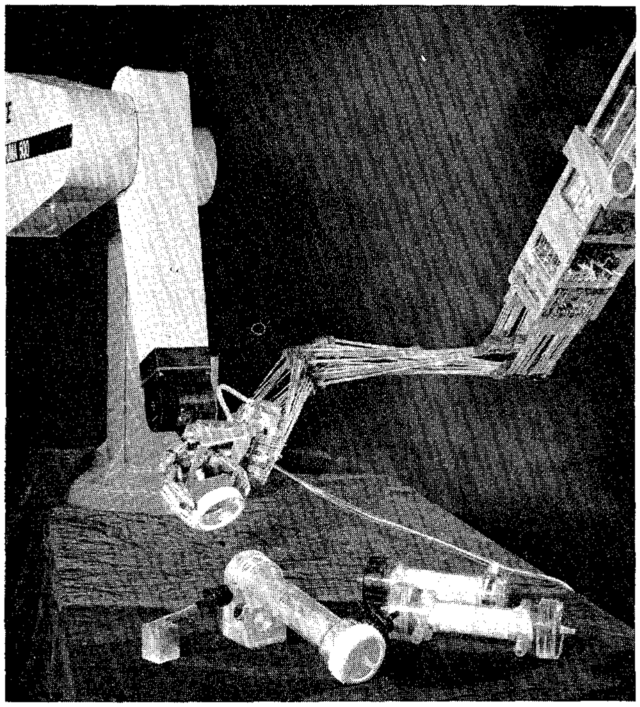

Figure 6A. Photograph of the Hand, Remotizer, Actuator Package, PUMA and positioning table.

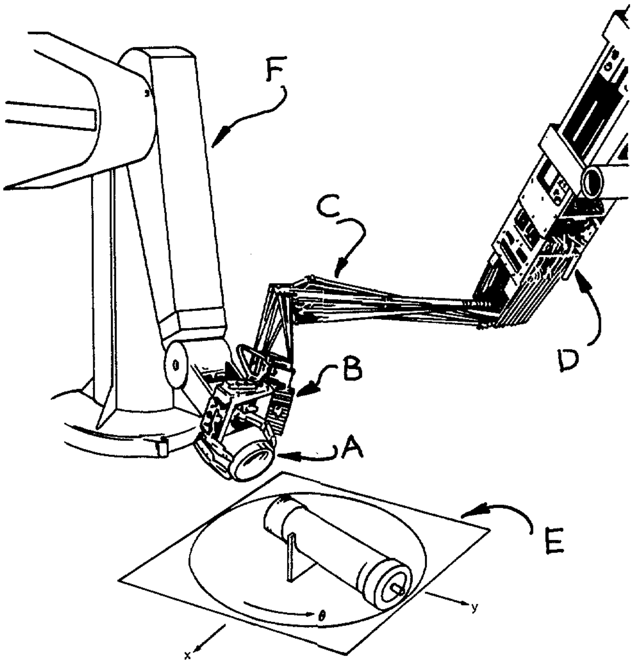

Figure 6B. Line drawing illustrating components in Figure 6A.

DH Structures and Joints. The Version II Hand, shown in Figure 7, is essentially a prototype system used for investigating issues in packaging, joint angle sensing, tendon routing, electrical interconnections and hand geometry.

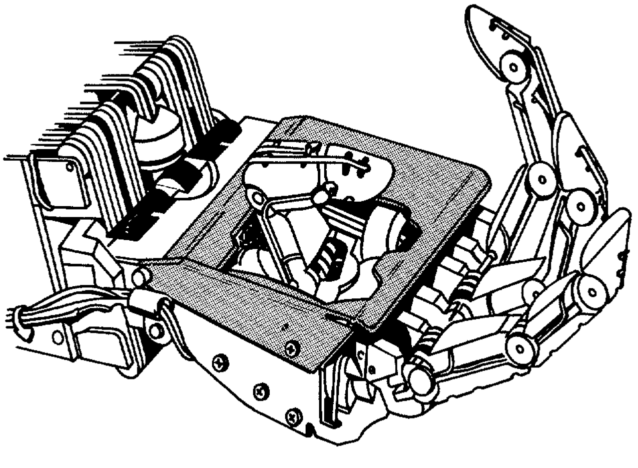

Figure 7. The Version II Utah/M.I.T. Dextrous Hand.

The Version II Hand was a predecessor to the Version III system shown in Figures 2A and 2B. Both hands include three fingers and one thumb, with each digit containing four joints. All three distal joints (1, 2 and 3) of the fingers and the thumb are capable of excursions from 0 - 95 degrees. The proximal, or 0 joint, functions differently depending on whether it is the base for a thumb or a finger. The 0 joint in the finger is capable of ± 25 degree motions and the 0 joint in the thumb is capable of ± 45 degree motions. The orientation of the base, or 0 joints, in the finger are illustrated in Figure 3. All elements of the Hand are machined 7075 aluminum with dual precision ball bearings installed at each joint. The hand and wrist include 184 low friction pulleys for the purpose of tendon routing. Joint angle sensors are located at the side of each joint, with their electrical connections running along lateral slots located at the neutral axis of each finger. On the opposite side of each finger are similar slots for the purpose of routing additional communication lines for external sensors.

Figure 8 illustrates the configuration of the wrist, which includes two perpendicular axes, implemented by a crossed yoke mechanism. A third orthogonal axis is made possible by axial rotation of the remotizer compression rods.

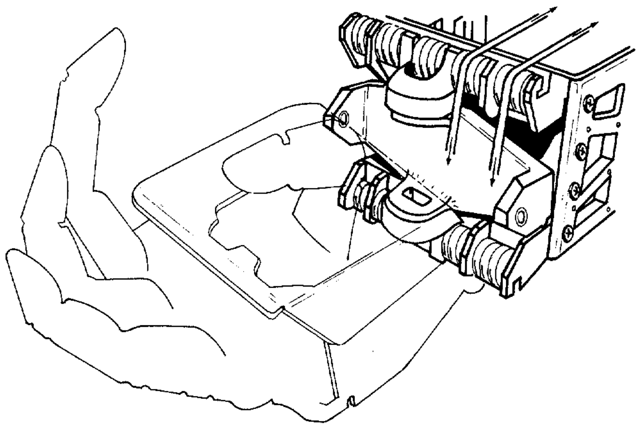

Figure 8. Configuration of the wrist in the Utah/M.I.T. Dextrous Hand.

Permissible deflections for the wrist are ± 45 degrees for wrist flexion/extension; ± 15 degrees for wrist abduction/aduction; and ± 135 degrees for wrist rotation. All three axes intersect at a central point in order to simplify inversion computations. Again, the wrist includes 32 tendon tension sensors located immediately behind the outer row of pulleys marked (A) in Figure 8.

Internal Sensors - Joint Angle and Tendon Tension. Figure 9 illustrates that each joint contains a sensor to measure angular deflection. Part A in the figure is a magnetically sensitive Hall effect device located in the proximal link, while part B, attached to the distal link, includes two cobalt samarium magnets operating in a dipole configuration. As the Hall effect device sweeps the magnetic field it produces an output current which corresponds to angular deflections between 0 and 95 degrees with a linearity within 5%. The Hall effect sensor system includes a number of advantages such as continuous output signal, high bandwidth operation, low friction, no mechanical contact, long life, and tolerance to surrounding contaminants.

Figure 10 illustrates one of the 32 tendon tension sensing systems located in the wrist. The pulley is positioned in order to perturb the path of the tendon such that tendon tension imposes a load on the cantelevered beam. A semiconductor strain gauge bridge detects beam strain and provides a linear output for tendon tensions from 0 to 30 pounds. Supporting electronics for both the angle and tendon tension sensors are located in the low level control system (LLCS) shown in Figure 17.

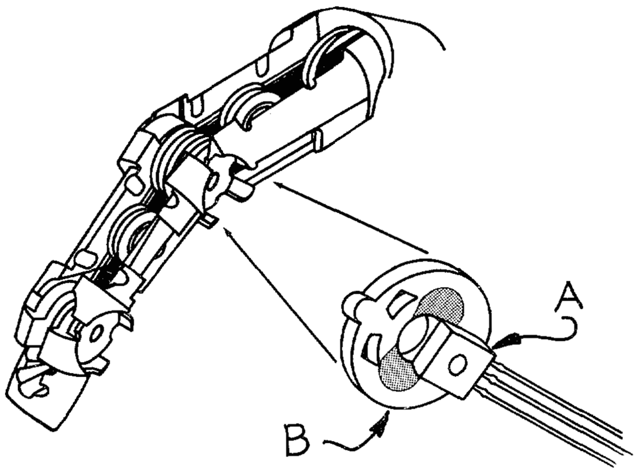

Figure 9. Configuration of the Hall effect sensor used to measure angular deflection of the joints.

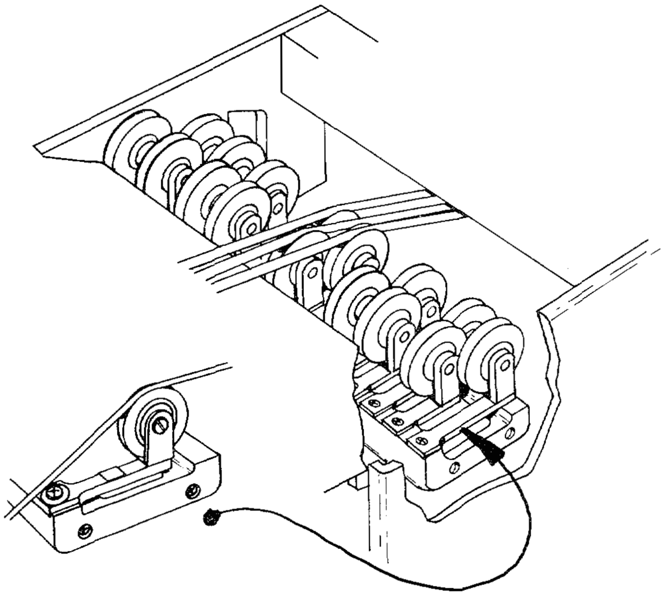

Figure 10. 32 tendon tension sensors located in the wrist of the Dextrous Hand.

External Sensors and Covering Systems. Figure 11 illustrates five removable segments which occupy void spaces in the finger structure. Each segment is approximately 1/10th of an inch thick and can be injection molded from either rigid or flexible materials. Depending on the particular experiment, selected sections of these rather disposable elements can be machined away to allow space for tactile sensing transducers; for example, detectors to sense direct contact, normal pressure, shear stress, temperature, etc. This approach maintains experimental flexibility so that various methodologies can be tried without committing to a specific geometry. Note that the entire system can be operated with the segments exposed or covered with a flexible glove to isolate internal components from unwanted environmental contaminants. As mentioned in the previous section, communication with external sensors will be provided via conduits which run along lateral slots in the fingers.

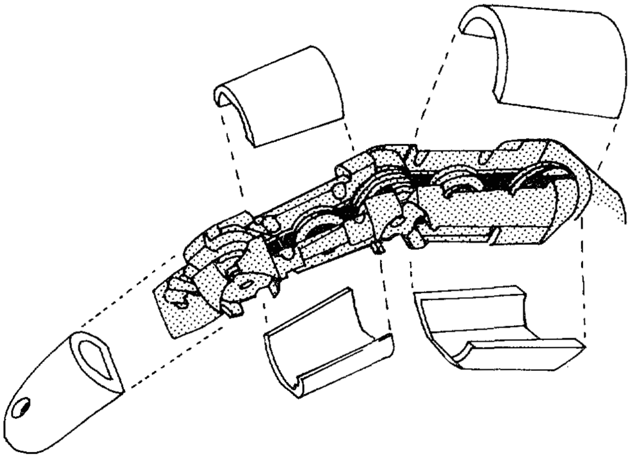

Figure 11. Five removable segments intended to house tactile sensing systems.

Actuators and the Actuator Package. As shown in Figure 12A, each joint receives two tendons, driven by actuators which consist of pressure controlling valves and low stiction cylinders. Each valve receives an electrical signal which commands a cylinder pressure. As described in References 1, 3, and 4, the signals are modulated so that the torque (differential tendon tension) can be varied simultaneously with cocontraction (sum of tendon tensions) of the tendons. The actual module used in the DH is shown in the line drawing of Figure 12B.

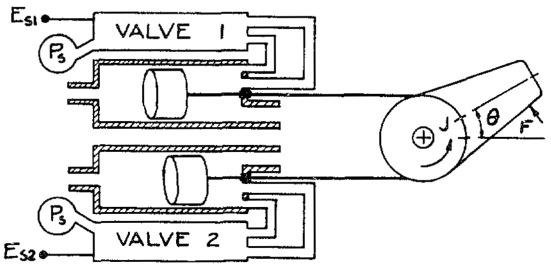

Figure 12A. Each joint is operated by two tendons which are tensioned by actuators consisting of low stiction cylinders and pressure controlling valves.

Each module contains two valves (A), two actuator cylinders (B), and two adjustable pneumatic dampers (C). Also, spring tensioning systems (B) are included within cylinders (B) to maintain tendon tensions when the system is unpressurized. Residual tension during inactive periods prevents misalignment of tendons which can, during operation, seriously impair tendon life. The cylinders for actuation and damping are constructed of

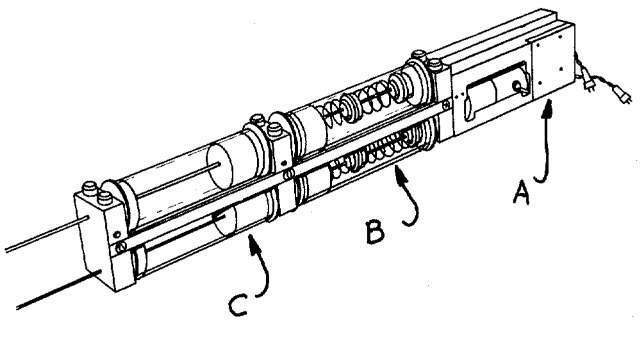

Figure 12B. A dual actuator module which includes valves, cylinders and dampers.

glass and close fitting graphite pistons. This configuration, operating at low pressures (50-100 psi), permits the elimination of seals, thereby minimizing stiction effects. Dampers, which operate in a pressurized mode in order to increase damping and minimize compressibility effects, are adjustable in order to allow a variable trade-off to be made between high frequency operation and stability during free-space operation. The actuator modules are compactly placed in a 4.25 x 4.25 x 24 inch rectangular assembly containing air manifolds and weighing 20 pounds, as shown in Figure 6. Electrical servo amplifiers for the system are contained in the low level control system as shown in Figure 17.

As further described in References 1, 2, and 3 and in Figure 13 each actuator consists of a two-stage jet pipe valve. The first stage is electrically driven to provide a pressure signal to a second stage such that an increase in primary stage pressure drives the second stage upper diaphram downward to deflect the jet pipe and increase piston cavity pressure. Piston cavity pressure is fed back to a lower diaphram on the second stage jet pipe which antagonizes the upper diaphram such that the valve behaves approximately as a pressure source modulated by input electrical current. This valve assembly is very fast. In fact, as shown in Reference 2 it can drive the pressure in the cylinder cavities, at maximum volume, with a flat frequency response up to 21 Hz.

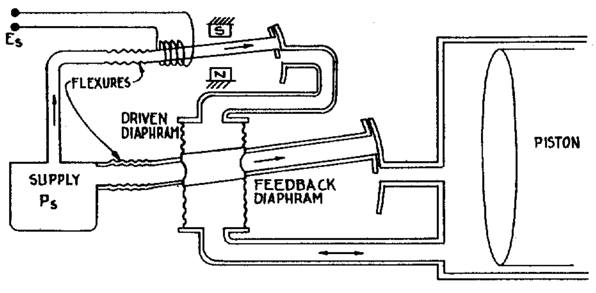

Figure 13. Schematic diagram showing the function of the two-stage electropneumatic, pressure controlling, jet pipe valve.

Tendons, Remotizer and Disconnection System. As shown in Figure 15A, the tendons in the DH are composite structures which consist of Dacron fibers woven around multiple longitudinal elements of Kevlar. The Dacron outer sheath serves to align and protect the internal load bearing Kevlar fibers. Tendons are routed throughout the hand via sequences of pulley-induced bends and axial twists as shown in Figure 4. Pulleys used have diameters of .95, .72, .49 and .38 inches with centrally domed contact surfaces in order to provide tendons with self-aligning properties.

The fixation of the ends of tendons is critical to system reliability and a number of termination approaches have been explored. Three successful termination methodologies are: 1) the permanent clip (C) as shown in Figure 14; 2) the age-old knot; and, 3) the overwrapped friction lock (A) in Figure 14 and Figure 15. The friction lock permits nondestructive and reversable adjustment of the tendons in order to initially locate fingers with respect to actuating piston positions. After adjustment, the tendon is locked via a supplemental machine screw. The molded section (A) shown in Figures 14 and 15 allows for easy, quick disconnect between actuator rods and the tendons.

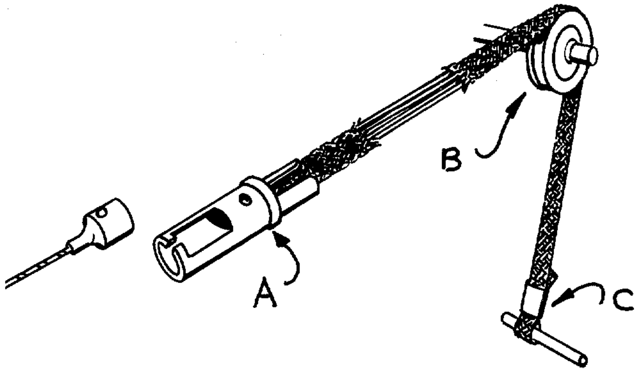

Figure 14. Tendons which are constructed of Dacron and Kevlar are routed over pulleys (B) and terminate either permanently as shown at point (C) or in a reversable manner shown at point (A).

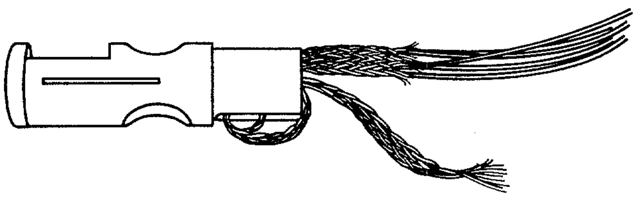

Figure 15. Injection molded component used to terminate tendons and provide quick disconnect capability.

Figure 6 illustrates the total remotizer which consists of four subsystems which each include: 1) rolling joints constructed of injection molded composite materials into which gears have been insert molded. The orientation of the two halves of the joint is maintained by coupling members and the gears which constrain the joint to roll in a manner which maintains tendon length regardless of angular deflection of the joint. Each rolling joint includes 16 pulleys for tendon routing which means that the entire remotizer utilizes 288 pulleys from the actuation package up to tendon tension sensors in the wrist; 2) compression rods which counteract tendon tensions and allow axial rotation in order to add degrees of freedom to the remotizer assembly; and, 3) eight tendons which run between the actuator package and the tendon. Note that the four subsystems must be flexibly tethered in such a way to maintain their general coordination while permitting simultaneous relative motion as the remotizing system is bent and twisted.

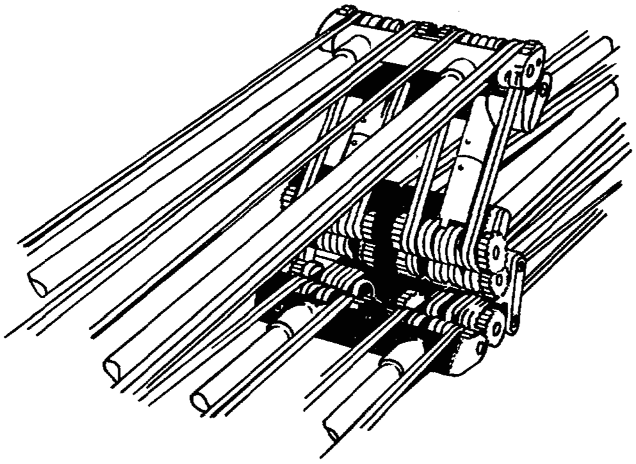

Figure 16A. Oblique view of the central joint (elbow) of the remotizer. Note four subassemblies operate in parallel to conduct 32 tendons from actuator to hand.

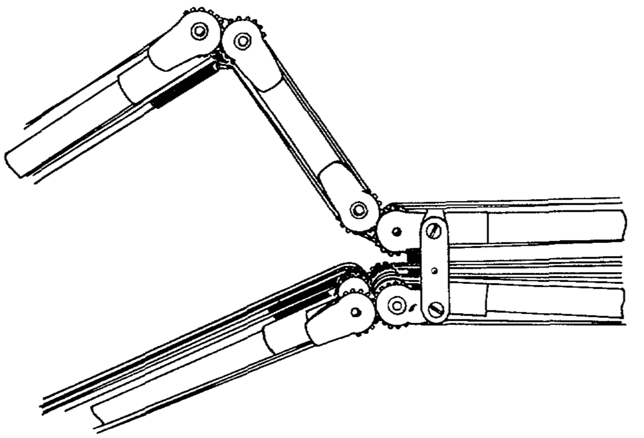

Figure 16B. Side view of the central remotizer joint showing rolling action of remotizer subsection joints.

Analog and Digital Computation System. Figure 17 shows the Low Level Control System (LLCS) which can stand alone to insure that all subsystems are functioning or receive complex analog inputs from higher digital control systems. The analog system is advantageous since it executes a of number servoing functions smoothly and with high bandwidth, thereby reducing computational requirements on the digital control system.

The LLCS includes 16 variable-loop-gain position servos to operate finger joints and 32 variable-loop-gain tension servos to modulate actuator behavior such that tendon tensions can be closely controlled. Amplification and signal conditioning circuitry is also included to: 1) provide current sources for driving pneumatic valves; 2) drive and monitor tendon tension sensors and drive and monitor joint angle sensors. For reasons of flexibility, system inputs include: 1) 16 inputs for control of angular position; 2) 32 inputs for control of desired tendon tension; 3) 16 inputs to vary position servo loop gain; and 4) 32 inputs to vary tendon tension servo loop gain. Also, a number of auxiliary inputs are available to control damping, cocontraction levels and to allow direct control of servo valve currents. The face of each of the 16 subsystems of the LLCS includes 13, proportional, multicolor light emitting diodes (LED) for the purpose of diagnostically displaying important system parameters. The console also includes 16 potentiometer inputs for the purpose of manually adjusting joint angles. The LLCS also provides analog outputs of all sensor signals generated within the hand.

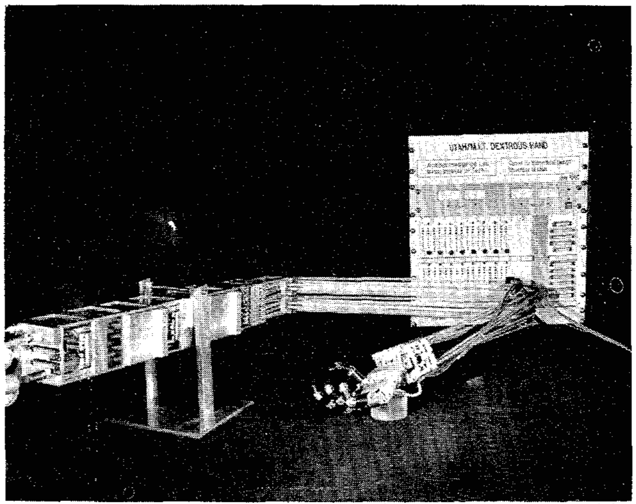

Figure 17. Low Level Control System (LLCS) which implements basic servo functions for the system and provides an interface to higher digital control systems.

The digital control system, which has been previously described in Reference 5, will only be briefly reviewed here. The system consists of five Motorola 68000 microprocessors, a Multibus card cage, 40 channels of digital to analog conversion and 320 channels of analog to digital conversion. All software development was accomplished on a VAX 11/750, utilizing the programming language "C." The system includes four finger controllers each doing all computations required for four joints. The system also includes a master controller which: 1) manages all system gains; 2) deploys data; 3) interprets primitive commands; and, 4) monitors the system for errors. High speed data taking and plotting have been accomplished via a PDP 11/44.

System Performance

Providing a comprehensive description of the performance of various system elements is a lengthy task and is beyond the goals of this document. Additional information regarding performance can be obtained via References 1, 2 and 3. However, in order to provide the general impression regarding the performance of an individual finger, Figures 18A and 18B have been included. Figure 18A illustrates the combined step response of joints 0, 1, 2, and 3. The finger in this circumstance executes a grabbing motion, combined with a side sweep due to the 0 joint motion. The approximate rise time can be seen to be approximately 70 milliseconds.

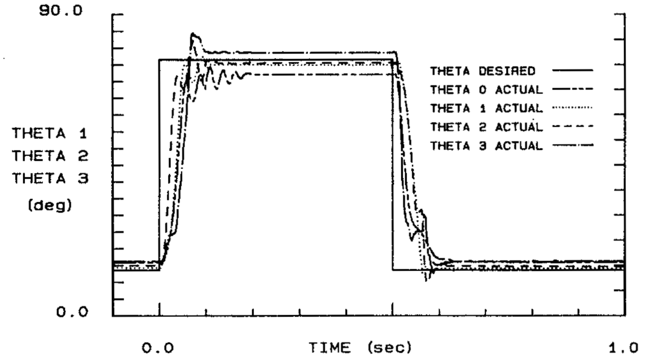

Figure 18A. A complete Version I finger as outlined in Reference 3.

Figure 18B illustrates the gain ratio for a finger executing a motion similar to forward running. Joint 1 is driven by the function A_0 sin (ωt), while joint 2 and 3 are driven by the function A_0 sin ($\omega t - \pi / 2$) where A_0 is 60° on joints 1, 2 and 3 and 45° on joint 0 and ω is the frequency. Note that this system exhibits a relatively flat response up to frequencies of approximately 8 Hz. The output is less well behaved but substantial at frequencies up to 30 Hz. The somewhat unwieldy behavior in the range from 10 to 30 Hz is a result of coupling motions between degrees of freedom which can be reduced via compensation in the controller if desired.

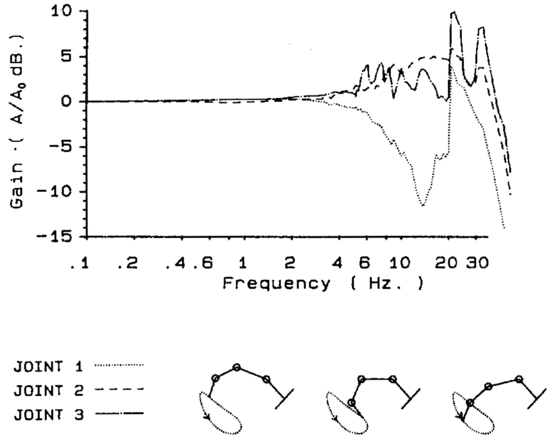

Figure 18B. Gain plot for an individual finger executing a forward running motion as described in Reference 3.

CONCLUSIONS

Previous sections have reviewed the development and characteristics of the Utah/M.I.T. Dextrous Hand which promises to be an effective tool for the investigation of issues in machine manipulation. The DH, together with its wrist and remotizer includes over 25 degrees of freedom thereby providing a rich environment for experimentation. The system exhibits high electromechanical performance in both active and passive operation so that both high and low speed manipulation procedures can be explored. Finally, the system has been designed for maximum reliability in order to allow experiments of significant complexity to proceed without interruptions due to machine failures.

Now that the hand and its low level control system are in existence, a number of experiments will begin aimed at understanding higher control system issues such as task definition, manipulation strategies, grasping functions and the collection and utilization of comprehensive sensory information. With equal importance, work will also continue towards understanding issues related to machinery so that future manipulation systems can be designed to produce high performance, with substantial reliability and at a reasonable cost.

The paper also reviewed a number of important issues which impinge on the development of future systems. Of particular importance to future work will be: 1) understanding appropriate goals; 2) developing approaches for the effective management of directed research efforts; and, 3) achieving a balanced focus on both theoretical and practical issues.

ACKNOWLEDGEMENTS

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