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Man-Equivalent Telepresence Through Four Fingered Human-Like Hand System

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Abstract

The paper describes a newly developed mechanical hand system. The robot hand is in human-like configuration with a thumb and three fingers, a palm, the wrist and the forearm in which the hand and wrist actuators are located. Each finger and the wrist has its own active electromechanical compliance (AEC) system, allowing the joint drive trains to be stiffened or loosened. This mechanism imitates the human muscle dual function of positioner and stiffness controller. This is essential for soft grappling operations. The hand-wrist assembly has 16 finger joints, three wrist joints and five compliance mechanisms for a total of 24 degrees of freedom (d.o.f.). The strength of the hand is roughly half of the human hand and its size is comparable to a male hand. The hand is controlled through an exoskeleton glove controller that the operator wears. The glove provides the man-machine interface in telemanipulation control mode: it senses the operator's inputs to guide the mechanical hand in hybrid position and force control. The glove receives positional feedback from the mechanical hand. A new state of the art control and electronics design was developed for this hand system. Communications between glove and hand are by fiber optics cables. The hand system is intended for dexterous manipulations in unstructured environments. Typical applications will include work in hostile environments such as space operations, nuclear power plants or any other complex remote operation.

Introduction

Current day robots use one d.o.f. end effectors to hold objects or tools. Future robots will need skillful manipulation capabilities to manipulate objects within the hand. Classical manipulation examples include turning an object within the hand, holding and squeezing a plier with one hand or squeezing the trigger of a power tool while holding it at the same time.

These manipulation capabilities can only be achieved through dexterity within the hand. Hand dexterity requires a multi fingered hand where the fingers have to be able to move in different directions so that an object can be manipulated and regrasped within the hand and not just clamped as is the case with common end effectors.

A fingered hand gains additional multifunctionality due to its versatility: Two fingers can form a small size sub end effector. The articulation of the hand and the small finger size allow it to reach in between or around obstructions. Furthermore, the thumb can be rotated outward to form an open faced hand. The object size to be handled is thus not restricted by the maximum opening of the two opposing claws as with common grippers. Also, the hand can conform to the object's shape, providing a secure wrap-around grasp. A lock-in grasp requires less clamping force, enabling the handling of delicate or fragile objects.

To build a hand that incorporates the above mentioned functionalities was the challenging task of this research. It required new approaches in the mechanical, control algorithm and electronics designs. The key development items that are essential for the successful operation of a dexterous hand are briefly outlined below. It is followed by a description of the overall system and all individual elements of the hand system. The paper concludes with a few remarks about our future plans for this development.

Key Development Items based on Functionality

Mechanical design, kinematics: A robot hand performs mechanical work. Its manipulation skills depend as much on the mechanical capabilities of the hand as it depends on its control. State of the art designs for the four main mechanical sections of the hand system were thus implemented. The four sections are: 1) The hand-wrist assembly with power transmissions to every joint. 2) The hand-wrist actuators, the compliance mechanisms and all hand sensors, all located in the forearm. 3) The control glove, fitting the human hand and containing the glove's force sensors. 4) The glove's positional feedback actuators and position sensors, contained in a remotely located box and linked with the glove through flex cables. Hand and glove are kinematically nearly identical to the human hand

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to enable human-like manipulations.

Hand control: To control this complex hand, having four parallel by four serial finger joints to execute coherent hand manipulations through computer control alone is currently an impossible task. This fact led to the anthropomorphic configuration to which the operator's brain can easily relate since it is kinematically identical to the human hand. With this configuration, any complex hand manipulation can be performed by a human operator who wears a control glove. A glove controller that can remotely guide the hand in a simple and userfriendly way thus became part of the hand system. Even though the exoskeleton glove looks very different from the hand, it is kinematically nearly identical to the mechanical hand to enable joint to joint mapping for direct hand control through the glove, thus minimizing computational efforts for joint coordinate transformations.

Active electromechanical compliance: AEC in essence provides the mechanically equivalent secondary function of the muscle which is to control the stiffness of individual fingers or the wrist. This capability is incorporated in the mechanical hand through compliance servo mechanisms that adjust the stiffnesses of individual linkages in the joint's actuator system. Sensing the amount of deflection in the flexible elements of the compliance mechanisms allows to determine the amount of applied force. This in turn allows hand control in force control mode. Thus, the system can operate in hybrid position and force control. A more practical consequence of AEC is the capability to align the hand snug tight around an arbitrarily shaped object while in the soft touch or compliant grappling mode. This could otherwise not be done, not even with the glove controller.

Sensing, electronic control: The sensory feedback provides the operator with a realistic feeling of operating on location: To effectively guide any complex manipulation task, it is necessary to provide the operator with positional feedback at every joint, especially since many finger linkages will not be visible to the camera while grasping an object. Therefore, the master control glove was equiped with positional feedback at every joint. The glove also has force sensors enbedded at every joint so that the operator can simulate exerted hand forces. A new control algorithm was developed that incorporates the active compliance features into the hand control. Due to the complexity of the multi fingered hand control problem, the initial experimentation will be entirely in teleoperational mode through the glove controller.

Overall System Description

The overall system is depicted in Fig. 1. It is subdivided into three subsystems: 1) The master, containing the glove, the glove back drive box, the glove's sensors and the local control electronics for hand and wrist. The glove electronics is located on the glove drive box. 2) The control computers, power supplies, power amplifiers and the user interface terminal, all located at the control console. 3) The slave subsystem, containing the hand-forearm, the hand's sensors and the local hand-wrist electronics. All sensors and the hand and wrist electronics are located inside the forearm. The number of motors and sensors at both, the master and the slave subsystem are indicated in the figure. Fiber optics communications lines link master, control computers and slave subsystems. An additional fiber optics line handles the communications between the computers dedicated to master or slave.

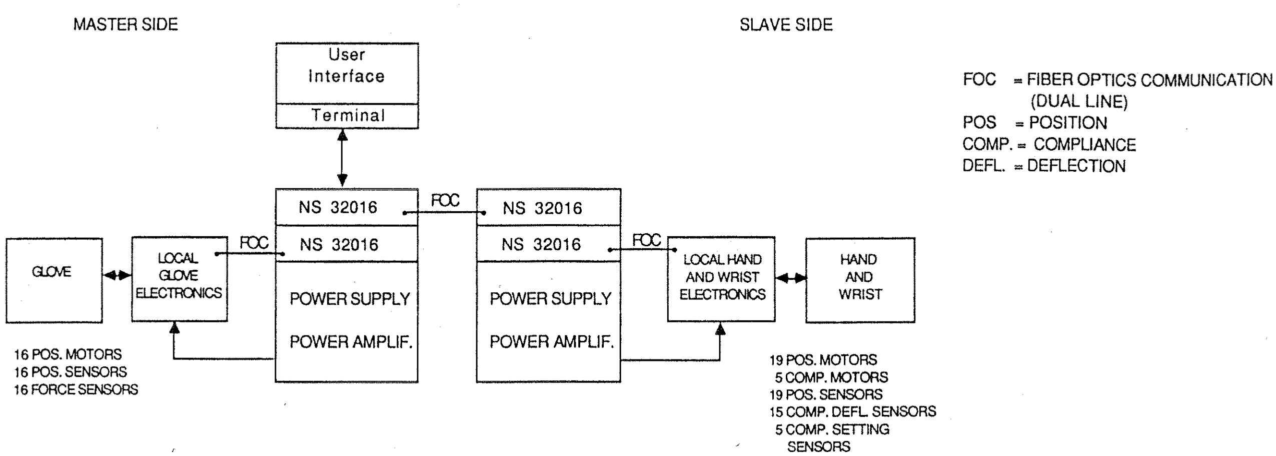

Fig. 1 Hand System Overall Block Diagram

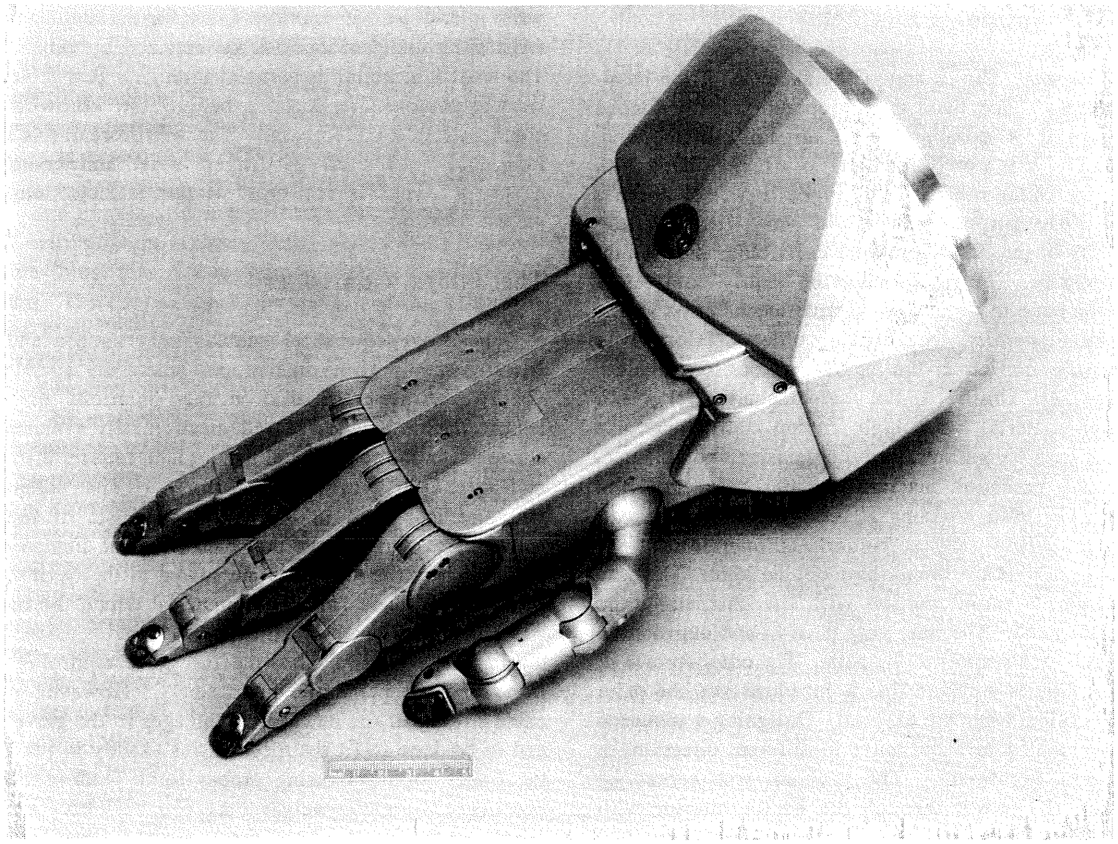

Fig. 2 The Mechanical Hand

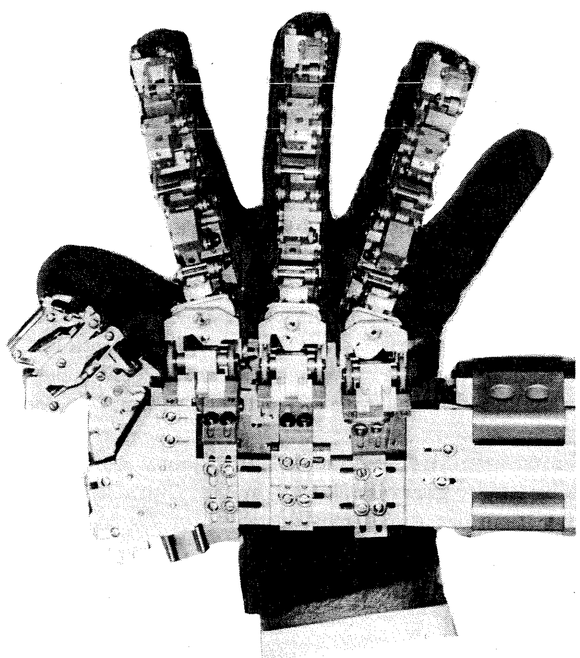

Fig. 3 The Glove Controller

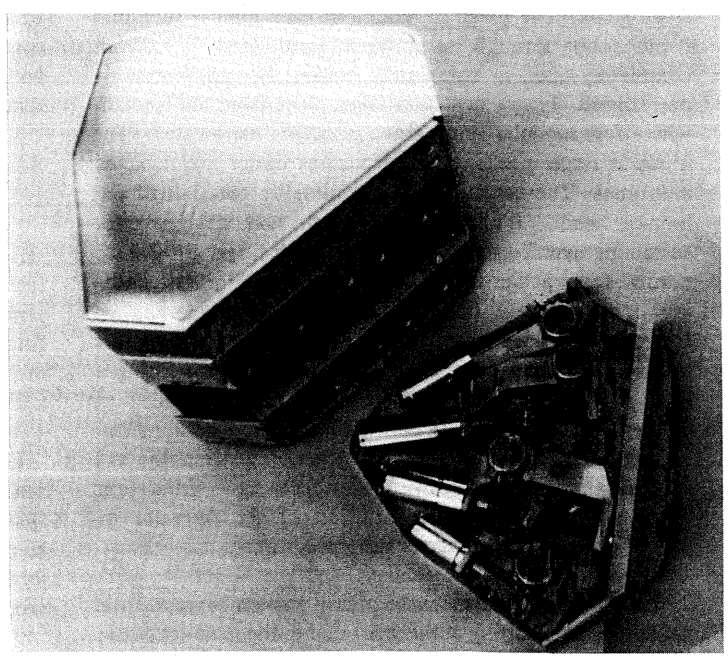

Fig. 4 The Backdrive Actuator Box

Hand Description

Hand features: Fig. 2 shows the skeleton of the hand-wrist assembly. The hand is anthropomorphically shaped and in size it is comparable to an adult male hand. Kinematically, it is nearly identical to a human hand with the exception of the missing fifth finger. It was determined that the little finger would add very little to the functionality of the hand but much to its bulkiness, weight and complexity. The hand skeleton nearly completely encloses the hand to protect its internal mechanisms and to prevent joint jamming by intruding objects. Composite materials will soon cover the hand's surfaces to provide a surface softness similar to the human hand of skin and flesh. This material has a high friction coefficient for a secure grip and its softness provides passive compliance. All parts are precision machined to ensure accuracy of motion. Each joint contains at least two miniature ball bearings to ensure nearly frictionless operations. Of particular interest is the thumb-base double joint: The base joint provides a radial motion with the axis along the length of the hand. The next joint is an in-and-out rotation of the thumb with respect to the palm. The outer surface of the double joint is a sphere that is inbedded into the palm so that no critical parts are exposed. Designing a sequence of actuated small joints that move in different directions is an engineer's nightmare. The problem was solved by transmitting the power through the hand's interior with flex cables and transferring the power to the individual joints through pulley drives. Each joint operates independently of all other joints. No compensatory motions are necessary at other drive units to move one single joint alone. This simplifies the control problem by enabling a one-to-one correspondence between master and slave joints. The speed of motion of each joint is such that it can rotate through its entire motion range (i. e. from completely open to completely closed) in approximattely one second. Finger actuation takes place from the forearm where four modular finger-drive packages are located. The modular finger package design insures easier maintenance and repair. The hand's strength is roughly one half of the human hand. It's holding strength was designed for sustaining over 2 kg normal force at each finger tip, 3.5 kg normal force at the thumb. The lateral holding strengths are approximately one half of the normal strengths. However, if a load is applied close to the finger base, the load capacity increases. Several fingers can share lifting a load, thus further increasing the overall load capability of the hand. Large loads will be handled by the palm. As can be seen, the load capacity and clamping strengths are configuration dependent. Optimal strength utilization depends on the skill and intuition of the operator or programmer. The hand alone weighs 0.9 kg.

Wrist/forearm: The mechanical arm portion deviates from the human arm starting at the wrist due to the need for larger wrist-arm cross sections. It enables larger wrist torques, the passage of the many flex cables to pass through the wrist interior and it provides space for the actuators. The wrist pitch and jaw motions are actuated by cable drives. The wrist roll motion is actuated through a gear drive. The wrist actuators are located behind the elbow axis to counterbalance the forearm. The wrist/forearm is 95 cm long and houses all 24 finger, wrist and compliance actuators. The forearm cross section is 23x29 cm at its widest location.

The Glove Controller

The glove controller enables very simple and user friendly man-machine interactions where the operator just simply performs the desired manipulations manually: Human hand inputs are sensed, electronically evaluated and conveyed to the mechanical hand which repeats the motion and/or exerts a proportional force. The mechanical structure is shown in Fig. 3. It consists of four bar mechanisms and pulleys that backdrive the human finger joints. The structural parts are sowed to the outside of an actual glove made from cloth material which the operator wears. Numerous size adjustments can be made at the mechanical structure, allowing the glove controller to be fitted to most percentile male hands. However, custom made sowing of the mechanical linkages to the glove fabric had to be done to fit the mechanisms exactly in place over the finger joints, assuring proper force feedbacks to the operator. The glove weighs 1 kg. Its backdrive actuators are shown in Fig. 4. They are housed in a box with four modular finger drive packages (drawers). Each drawer has four actuators and is assigned to one of the four fingers. Flex cables transmit motion and power from the drive packages to the glove. The flex cables are not shown in the pictures. The mechanism outside the palm near the little finger is a quick snap-on attachment to an arm controller. The glove contains no wrist controller. As will be mentioned later, the wrist is controlled by the master arm controller.

Sensing

Hand sensors: All 19 hand-wrist joints are position sensed. The first joint of each finger is noncompliant, that leaves 15 compliant joints, requiring 15 deflection sensors. Each of the five compliance systems (one for each finger, one for the wrist) senses its compliance setting, therefore there are five compliance sensors. All hand sensors are located at the drive trains in the forearm.

Glove sensors: Each of the 16 glove joints are force sensed by strain gages implanted in the joint's linkage system. It allows direct measurements of the applied human finger joint torques at each location. All master arm joints are position sensed at the drive system. Some of the sensors are visible in Fig 4.

Control

A novel control algorithm was developed for this hand system. The control diagram is depicted in Fig. 5. The electronic components are grouped into several nodes at master, slave, and control console as can be seen in Fig. 1. The computing architecture is a fully synchronized pipeline with unique methods for data handling and communication. Processing is based on the NS 32016 microprocessor. Up to 3 million instructions per second can be handled by the current configuration. This is enough computing power for this telemanipulation system, which has matching master and slave joints that reduce the computational effort to a minimum. The control loops operate at 500 Hz. This rate provides high-fidelity control for telemanipulations. The main tasks the processors have to perform are sensory feedback evaluations and joint and compliance motor control. The mathematical computations amount to only a small percentage of the overall processing endeavor. The power amplifiers are of the PWM type and can handle motors of over 100 W at servo rates of 1000 Hz. Sensor data from the wrist and the fingers are locally processed. The local controllers receive control commands through fiber-optics cables. All internode communication of all hand and wrist joints is performed by 5-Mbaud fiber-optic dual lines. The master and slave have two local processor boards each. One such board is shown in Fig. 6. A more detailed description of the electronics can be found in (1).

Operational Principle

Fig. 5 shows the control diagram of an active electromechanical compliant joint controlled in teleoperation. The upper portion is similar to the classical control diagram for teleoperators in position control. However, the drive input in this case is a force signal that the operator must provide by pushing slightly against the glove joint which is strain gage sensed. It activates an electrical response signal that drives the slave. The slave joint will move in proportion to the input signal strength if it is not being restrained. The slave's position is sensed and the master joint backdriven according to the slave's position. The master joint always matches the slave joint's position so that the operator never looses the perception for the slave's position at any time during normal operations. The master joints are thus non-yielding with respect to direct operator inputs and will only move if they receive backdrive signals from either slave, or, in the disconnected slave mode, through force input signals from the master.

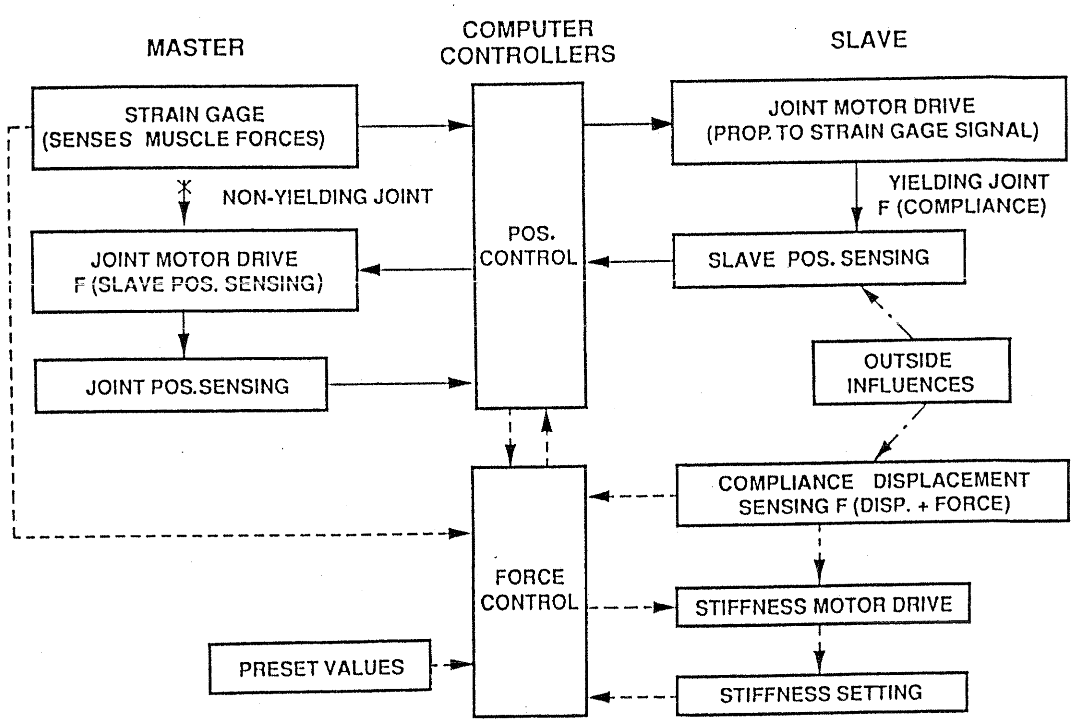

Fig. 5 Control Algorithm for Coompliant Joint

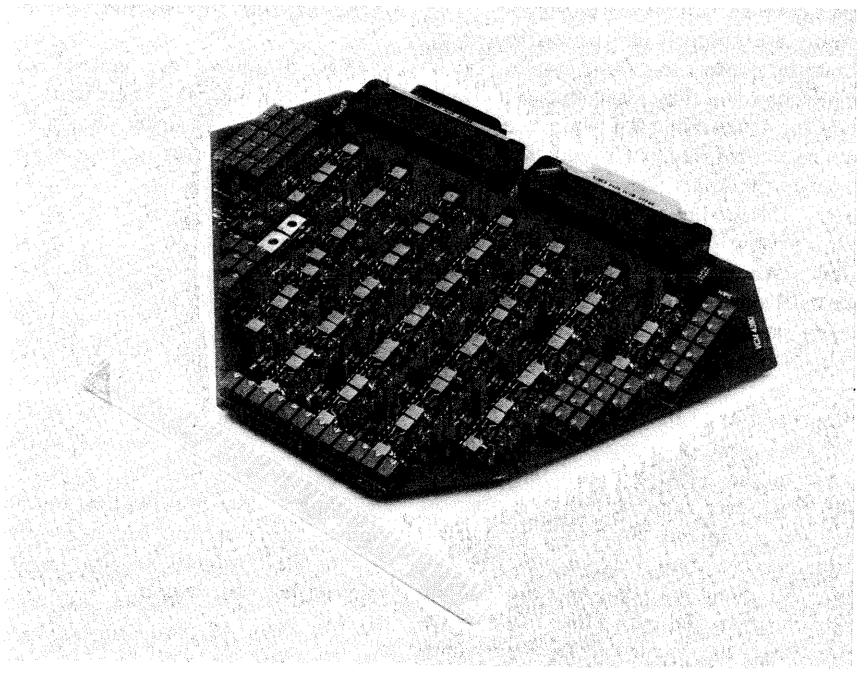

Fig. 6 Typical Hand or Glove Local Processing Board

Should an object be encountered that prevents a joint from moving further, it will deflect the compliance mechanism which in turn will automatically switch this slave finger (or the wrist) into the force-control mode. The slave's joint torque is now proportional to the torque which the operator exerts at the corresponding master joint. If the operator increases forces or torques to push, pull, or lift something, the joint compliance will be stiffened automatically just like the human muscle system stiffens itself while handling heavy loads. This can easily be accomplished in software by disallowing the maximum allowable compliance deflection to surpass a predetermined amount.

Integration of Hand System with Robot and Robot Controller

For initial experimentation, the mechanical hand-forearm will be mounted on a PUMA robot: The standard PUMA forearm will be removed and the dexterous forearm mounted at the robot's elbow joint. The glove controller will be integrated into the Salisbury/JPL (2) hand controller. This 6 d.o.f. controller controls the robot's wrist joint for position and orientation.

Experimental Results

The hand system will become operational in mid 1992. It is hoped that initial test data will be available in time to be presented at the conference.

Future Work

Initial experimentation will take place with the hand system mounted on a PUMA robot and the glove integrated on the 6 d.o.f. hand controller. Subsequent operations will be performed with a 7 d.o.f. arm for which an anthropomorphically shaped robot upper arm will be built. An exoskeleton 7 d.o.f. arm controller has already been built. The expanded system will have 23 arm-hand joints for both, the master and the slave arms. The system will then be expanded to a full anthropomorphic dual arm-hand system. Targeted field applications include space work and in nuclear power stations.

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