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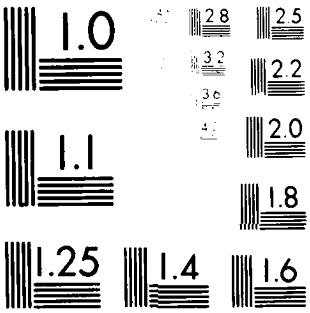

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FINAL REPORT

ACHIEVEMENT OF A SENSE OF OPERATOR PRESENCE IN REMOTE MANIPULATION

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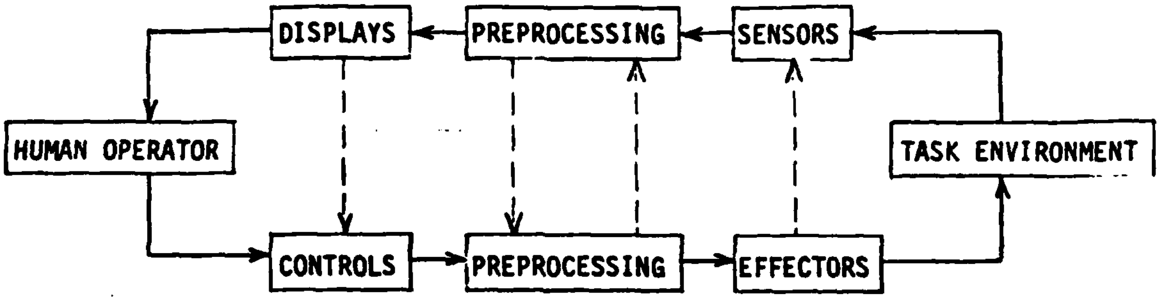


ELEMENTS OF A TELEPRESENCE SYSTEM

ABSTRACT

It was the purpose of this project to review the state of the art of the technology associated with remote manipulation with the intention of providing parameters by which the operator of the remote system could achieve a sense of operator presence. This psychological sense of "presence," or immediacy, reflects the extent to which the sensor, display and control technology can be made transparent to the operator. ~~The results of our survey indicate:~~

- The present sensor, display and control technology for remote manipulation is sufficient, if properly configured, to produce a laboratory prototype of a telepresence manipulation system.
- The manipulator arm technology, given impetus by interest in industrial robotics, is sufficient to provide the tight kinematic and dynamic loop required for effective manipulation.
- The articulated end effector and its interface with associated articulated master hand controller is an area requiring some design effort. There is sufficient technological power to support design work.

- There is a gap in the state of knowledge concerning the display of tactile and proprioceptive information to the operator. Empirical data are required to specify the necessary and sufficient display densities for distributed tactile information, the intensity and method of display of such information, the required fidelity, and the temporal encoding of the sensor data. Further investigation is required to specify the appropriate locus, i.e., distributed or endpoint, for display of proprioceptive information. Investigation is needed into the scanning range required for this position and force information.

- Specification of particular task environments will direct the research required to protect the manipulator and sensor from each environment's hostile elements.

We propose a conceptual design of a prototype advanced manipulation system that will demonstrate the sense of operator presence desired.

In conclusion, we identify the forces acting on the development of remote manipulation technology. Further, we poll a cross sample of the expert community regarding the present and future states of remote manipulator technology, and provide our opinion of relevant future research directions.

INTRODUCTION

Statement of Project Purpose

In this project, the state of the art of technology relevant to the achievement of operator presence in remote manipulation is reviewed, and emergent technologies in sensors, displays, controls and manipulators are surveyed to ascertain the significant developments required in these areas to achieve operator presence. The project concludes with a judgment concerning the most useful areas of research and development over the next ten years to provide the technological capability to project operator consciousness of a remote manipulator system to the site of manipulation.

We have placed emphasis on those areas directly related to the sensory/motor components of manipulation, i.e., systems that reflect knowledge about the environment by touch, pressure and force, and those systems that enable the manipulator to interact with the environment by position, rate and force control.

The project was not designed to be a compendious or encyclopedic review; rather, the scope of the project was defined in terms of an ultimate goal: the achievement of operator feeling of presence in telemanipulation. We have reviewed the technologies most likely to provide that presence. There are no breakthroughs required. The technological state of the art of known component subsystems appears to be capable of providing the information presumed to be needed to achieve a sense of operator presence. The state of our knowledge of how "presence" is attained, however, or what part of the available information will provide a high feeling of reality, is inadequate; so is the state of our knowledge concerning the man-machine interface in so intimate and complex an interaction.

Report Format

A conceptual design is detailed throughout this report in which are embodied the capabilities of the present state of the art as well as the requirements of the program to demonstrate an advanced manipulator system (AMS). Our intent in the conduct of our search through the component subsystem technologies was to find those components most likely to support a system design for advanced telemanipulation. The search for, and development of, a system design were interactive, so this report is structured in a design format; we review relevant technologies and research areas as appropriate to each stage of system design.

Purpose of Advanced Manipulator System

The use of an advanced manipulator system is intended for environments too hostile or too remote to permit immediate operator function. Previous experience indicates that introduction of a mechanical manipulator between the operator and his manipulation task results in serious degradation of performance (Corliss and Johnsen, 1968). A major purpose of a tight sensory and cognitive coupling, to the point where the operator feels present at the task site, is to reduce or eliminate that performance deficit. The manipulator system, therefore, must map salient information concerning system performance and environmental conditions into the range of sensibility for the human operator, and the human operator output of control information must be mapped accurately to command structures appropriate to advanced manipulator system control. This one-on-one mapping process itself introduces the first design requirement in the advanced manipulator system, viz., the translation of data from a remote and hostile environment to one available to operator experience.

Requirements for Mapping Remote Environments to AMS Operator

In any man/machine system, there is a requirement to specify parameters of performance contributed by the man, the machine, and the communication interface. In the proposed system, the interface between man and machine is designed to be as intimate as required to make the operator psychologically unaware of the machine's existence. Engineering performance models have achieved impressive results in describing the human operator as a black box whose characteristic function is that of an integrator and time delay of a quasi-linear nature (McRuer and Krendel, 1974). Such models are not sufficient to specify the informational feedback and feed forward required in the advanced manipulator system. While it is sufficient to rely on the human operator to integrate the raw sensory input of experience, it is imperative that he be provided with appropriate inputs displayed in a form available for effective operator encoding. This raises the formidable issue of the nature of human information encoding in the neuromuscular and kinaesthetic systems. The state of the art of knowledge of such encoding is reviewed in the body of this report; here we will detail basic system constraints in man-machine mapping.

Safety Factors

The primary requirement in appropriate mapping is that of safety. The human operator must be informed of potentially destructive situations for the remote manipulator system, and, since the manipulator is operating in a hostile environment, the human operator must be shielded from the destructive elements of that environment.

Shielding can be achieved at a number of levels:

1) filtering of the transmitted information to levels physiologically appropriate to the human operator
2) software decoupling of the operator from the manipulator in emergency situations
3) hardware decoupling of the human operator from the manipulator as a back up system.

Informational Mapping of Manipulator to Operator

The human operator as an information processor has certain limitations. Basic system constraints include:

1) Limited Display Density

The areas of maximal sensitivity for touch, vibration, heat and pressure are in the fingertip and hand region. These regions have little area for display. They are also highly articulated, and consequently easily encumbered by noninvasive displays.

2) Limited Channel Capacity

The limitation of human operator capability to update information from a single source or to monitor information from several sources is well documented (Broadbent and Gregory, 1963; Hick, 1952; Taylor, et al., 1967; Kristofferson, 1969; Moray, 1979).

Informational Mapping of Operator to Manipulator

In this transformation, the enormous range of operator function and dexterity must be translated to the control configuration of the manipulator system. The operator must be kept tightly linked with the remote manipulator while consideration is paid to manipulator dynamics and kinematics as well as to tactile and proprioceptive sensitivities. The relevant technologies are reviewed in the body of this report in the sections dealing with sensors and with controls.

REVIEW OF THE STATE OF THE ART

Overview

In keeping with contractual obligations to collect and review current literature pertaining to remote handling, sensing and display technologies relevant to manipulation in remote hostile environments, this review will be concentrated on both hardware and information processing aspects of remote manipulation. This state of the art survey follows parallel development in investigation of human operator sensitivities in a dynamic, interactive control loop, as well as the development of hardware in areas of sensors/displays and manipulators/actuators/controls.

Limitation of Scope

It should be noted at the outset that our directed state of the art survey was restricted to unclassified information, literature and materials. We are, then, unaware of most classified activities in remote manipulation, sensors and displays. We have, however, located sources of information which, while not directly available to us, may be accessible to the U. S. Navy.

Sensors, Displays and Controls

To assess the state of the art relevant to the design of an advanced manipulator system, it is necessary to determine what sensory modalities and physical qualities will be significantly beneficial to achieving operator presence. A primary consideration is that the human operator is limited by his sensory and effector capabilities and the information input-output of the advanced manipulator system in the remote task environment is constrained by the technology state of the art. The physical qualities and modalities of interest include:

- Position
- Force/Torque
- Touch
    - Contact Recognition
    - Pressure Distribution
    - Slippage/Texture
    - Pain (Nocioreception)
- Electromagnetic Radiation
    - Heat
    - Visual Imaging
    - Spatial Imaging
    - Other Ranges of Spectrum

While all of these may be of potential value in the advanced manipulator system, not all are of equal importance in designing a remote presence system.

Sensors

Position Subsystem

Perhaps the most basic requirement for a purposive remote manipulation system is position control. In a master-slave manipulation configuration, the orientation of the master or control arm matches the orientation of the slave arm in the task environment. The position of the operator's arm and hand is both the means of control of the remote manipulator and the display to the operator of the manipulator's position. Thus, in the position subsystem, display and control are inextricably linked.

Human Operator Capabilities in Limb Positioning Tasks

The data concerning the anatomy and morphology of those receptors that subserve limb position have long been established, as have the data on the structures presumed to be associated with touch sensations of various types. Gross human anatomy and the techniques for its study at a macro level have changed little over the past 15 years; the publications cited are considered the state of the art of knowledge in these areas. This firmly established data base of anatomical considerations unfortunately is not accompanied by corollary knowledge concerning the physiological and purposive functioning of the structures.

In an early but far reaching study of the relations of manual and automatic control, Kelly (1964) concluded that a major value of the human operator in a control system was his ability to predict the future performance of the system on the basis of an internal model of the controlled system. As Kelly puts it,

> Manual control systems function to reduce the difference between what an operator wants to happen to a controlled variable and what he thinks is going to happen unless he institutes a change.
>
> Kelly, 1964, p. 41

The difficulty in learning to control a complex system like a remote manipulator (aside from the inherent physical limitations of the system hardware) is learning to predict the performance of the system under a given control configuration, to wit,

> The ability to predict a system's performance is in major respects the same as an ability to control the system.
>
> Kelly, 1964

The rationale behind the attempt to induce a psychological sense of operator presence in remote manipulation is to assure that the operator is able to predict the performance of the remote system as if it were his own physical system. The sine qua non of this attempt is to provide the operator with feedback and feed forward capabilities that closely match those of the neuromuscular system.

Human Operator Limb Position

It is in the areas of fine position and force control that the human operator displays remarkable ability to make fast and accurate complex sequences of motion under various conditions of load or perturbation. The physiologically tight link between the muscle effectors and receptors is likely to account for this ability. It is our hypothesis that the achievement of operator presence and improved performance in manipulation is critically dependent on the ability to maintain a tight link between the human operator and the remote manipulator.

There is an ongoing controversy over the relative contribution to limb position and timing of two different sensory systems. In one view, joint receptors are held to be the positioning elements. In an alternate view, there is growing evidence that muscle afferents are contributory to and sufficient for joint positioning. Resolution of this controversy is relevant in that critical sensitivity to position rather than dynamic load makes different demands on the feedback modalities provided the human operator, or at least affects the priority of that feedback. Both receptor systems are reviewed here. The controversy has been reviewed by Kelso and Stelmach (1976), and more recently by Kelso, et al. (1980).

The priority and sufficiency of joint receptor information in limb positioning is supported by Adams (1977) and Roland (1978). Their argument finds support in the following physiological characteristics:

- Golgi tendon organs located in the ligaments (rather than in the tendons) are unaffected by muscle stretch, thence provide joint location as well as direction.
- Ruffini endings signal speed and direction of movement, affected by muscle tension may differentiate between active and passive motion.
- Pacinian corpuscles detect small motion acceleration.

Detailed research to prove the sufficiency of the joint receptors is beyond the scope of this report. Briefly, however, the methodology of such research is to selectively decouple the other available feedback mechanisms and then examine the movement pattern produced in the reduced preparation. This type of experimental evidence, reviewed and demonstrated by Kelso, et al. (1980), with neurochemical manipulation by Clarke and Burgess (1975), lends increasing support to the contribution of muscle afferents to positioning and to timing of limb trajectories. The basic physiological evidence is developed as follows:

- Primary and secondary spindle afferents form a segmental as well as transcortical feedback loop with information regarding muscle tension and load conveyed (Evarts and Tanji, 1974).
- Golgi tendon organ in series with muscle conveys information regarding muscle stretch.
- Alpha-gamma coactivation loops may serve as the load and position servo controller (Merton, 1964; Matthews, 1977).

The muscle afferent supporters contend that terminal location of the arm/hand in space is represented as a steady state condition of the muscle system. The kinematics of movement are thus determined by the inherent dynamics of the muscle/arm structure (Bizzi, et al., 1978a,b).

In addition to the variety of mechanisms providing position information, there is a variety in the motor control patterns used to achieve that position. Most relevant to our project is the change in the innervation ratio from proximal to distal musculature. The number of muscle units controlled by a single motoneuron decreases in the more distal body part. Functionally this implies an increase in control over the musculature associated with fine positioning and finger manipulation. Finger dexterity then commands a proportionately large amount of neural structure for control. In addition, the cerebrospinal communication is more direct in finger movement control than in other arm movements. The importance of finger dexterity is physiologically underscored.

For master-slave manipulations, fine position control approaching that of a human hand has not been constructed. This, however, does not necessarily mean that the technological capability does not exist. Impetus for the development of such control could be expected to come from the robotics industry, in the form of demand for dexterous end effectors. In robotics applications, the articulated hand would probably be computer controlled. At least until recently, the computations needed would be so complex as to make this impractical. The contention that articulation may be feasible, but is so far not done due to control problems, is supported in a recent interview with Victor Scheinman (Saveriano, 1980b). He discusses his activities in the early 1970's:

> ...I was working on a five-fingered hand which had 17 degrees of freedom. It turned out to be a very fancy piece of hardware -- but not controllable, which was one of my big disappointments. Coming out with good algorithms to control multi-jointed fingers with that many degrees of freedom was a difficult problem. In addition, I hadn't really worked out the tactile, or touch sense, which seems to be one of the keys to good localized manipulation capabilities, such as manipulating an object in a single hand.
>
> Scheinman in
> Saveriano, 1980b

By configuring an advanced manipulator system as a master-slave teleoperator, the control computation problem becomes irrelevant. Meanwhile, with the rapid decline in the cost of computing capability over the past several years, demand for an articulated end effector may be on the rise in the robotics industry. To quote a review of industrial robots appearing in the Summer, 1980 issue of Robotics Age,

> It is, however, the gripper of today's industrial robot that is one of the most limiting factors in universal robot utilization due to the lack of hand programmability. It is the weakest link of the robot's components. Extensive research and development is being done to produce a gripper that can handle a wide assortment of part configurations.
>
> Saveriano, 1980a

This statement refers to end effectors on computer controlled robots, rather than man-controlled teleoperators; there is no use of the term "anthropomorphic." The statement does point out, however, a deficiency that an anthropomorphic end effector would clearly remedy.

Examples of articulated end effectors include the "Belgrade Hand," a multi articulated hand with some compliance, designed as a hand prosthesis (Jaksic, 1973). This hand has a series linkage of three degrees of freedom for each finger of a five-fingered hand. The system is driven by an hydraulic pump located in the heel of the shoe of the user. Pressure at the heel dictates the sequence of grasp pattern as each of the fingers are recruited sequentially.

A three-fingered, cable driven device has been designed at the Electrotechnical Laboratory in Tokyo, Japan (Okada, 1979; Okada and Tsuchiya, 1977). The fingers of the Japanese effector are roughly equivalent to the thumb, index finger and middle finger. Each finger has joints corresponding to the joints in the human finger, plus one more near the base that allows for tilting the bending plane of each finger. Each finger can move independently of the others. Under computer control, this end effector has turned a sphere while holding it, and twirled a baton. This experimental model can hold 500 grams. It weighs 240 grams. Tactile and force sensors may be added to the device. It seems probable that additional fingers could be incorporated into an effector based on this design.

Force/Torque Subsystem

The control and sensing of force and torque is nearly as basic a requirement for an advanced manipulator system as the position subsystem, for without force information, even slight attempted changes in position by the operator may result in significant forces on the slave arm, so that it may damage itself or the object being manipulated. Force feedback allows the human operator to know when contact with obstructions has occurred; when properly scaled, feedback gives the operator an intuitive display of the strength limitations of the remote arm in the task environment.

Perception of force and load in the human is an integration of several sensations. Touch sensitivity provides cutaneous information that an object has been encountered and contacted. The muscle spindle embedded in the muscle fibers indicates degree of contractile effort required of the muscle to change position in the face of load. This information is hypothesized to be a function of relative changes in the coactivation associated with a particular muscle (Merton, 1964). The precision and sufficiency of this information in motor control is still being investigated (for example, see Valbo, 1974 or Kelso, et al., 1980).

In a human being, differentiating between force and position is difficult. This is also true for the force/torque subsystem of an advanced manipulator system. As Harmon says, we must accept

> ...the unwelcome fact that force cannot be measured directly; one can measure only displacement resulting from force, and thus the measurement is derivative, subject to error, hysteresis effects, etc.
>
> Harmon, 1980

As with position, display and control of force is inherent in the physiology of the human operator, and cannot be separated.

Commercially available master-slave manipulators generally incorporate force feedback. Such feedback is inherent in mechanically linked systems: If slave arm motion is limited by some obstruction, the human operator cannot move his arm until enough force is applied to overcome the resistance. When mechanical linkage systems were initially replaced with electrical linkage manipulators, this integrated feedback capability was temporarily lost. The state of the art electrically linked master-slave manipulator from Central Research Laboratory does have force feedback capability.

At the Electrotechnical Laboratory in Japan, an experimental manipulator has been constructed which is designed for direct computer control of joint torques (Takase, 1979). The robot arm has seven degrees of freedom: "shoulder azimuth and elevation, upper arm rotation, elbow angle, forearm rotation, and two orthogonal wrist pivots." To reduce arm mass, and so increase allowable payload mass, the arm is cable controlled. The actuators of each joint are remoted from the arm, and so do not contribute to its weight. The actuators are continuous torque magnetic power clutches. Only one motor is used to control the entire arm, linked to each clutch by timing belts. This mechanism requires less power than would the use of DC servo motors in place of the clutches. The arm was developed to demonstrate real time computer control of forces exerted by a manipulator. In fact, two of these manipulators were used together in such tasks as driving nails with a hammer, sawing wood, and turning a crank. While this arm is not human operator controlled, it is strikingly anthropomorphic, and may be adaptable to a force-reflecting electrically linked teleoperator system.

Various force sensors are available for application to the advanced manipulator system. Most of the sensors described in the Display Approaches section in this report are simply high resolution, high sensitivity force sensors, and so will not be discussed here. Under proper circumstances, many position transducers can act as force sensors.

Several "wrist-mounted" force/torque sensors have been developed for robotics and teleoperator applications. One such sensor, which Harmon (1980) refers to as the state of the art in force sensing, was built by Draper Labs; it consists of a Maltese Cross of four cantilever spring bars, each with four attached strain gauges. The forces are interpreted by computer. This sensor has been used to place pegs into holes with an 0.005 inch (0.0127 cm) tolerance. Bejczy (1980 a,b) reports using a force/torque sensor manufactured by Vicarm, Inc., of Mountain View, California. This sensor is also shaped as a Maltese Cross, and uses 16 strain gauges; the eight outputs of the sensor are resolved by computer into three orthogonal force components and three orthogonal torque components. It has a detection range of 0.5 to 300 newtons. Unimation sells a similar semi-conductor strain gauge sensor for $3500.

Touch Subsystem

Once gross control of the task environment is achieved using the position and force subsystems, mechanisms approximating the human sense of touch are necessary for fine manipulations. Touch is required so that the human operator can feel the contours of a manipulated object, and can know the quality of his grip on the object. Otherwise, manipulations must be clumsy, and the operator cannot know whether what he is holding is slowly slipping from his grasp. The touch subsystem is crucial to an AMS, yet little has been done to incorporate tactile feedback into teleoperators.

The human operator has an extremely sensitive and accurate system for touch sensing. A density of 700 sensors (of various types) per square mm of skin surface exists at the fingertips. The perception of touch is varied and is sensitive to the type of stimulus causing the sensation. The touch information available to the human operator in direct manipulation is considered here by the type of receptor:

Mechanoreceptors

Mechanoreceptors subserve information concerning the mechanical deformation of the skin. There are several types of sensors distinguished by differing morphology and sensitivity. We have divided these sensors functionally into sensors that distinguish between instantaneous changes in the system and those that signal continuous conditions:

Rapidly Adapting Mechanoreceptors
(provide transient touch information)

Pacinian Corpuscle

The Pacinian corpuscle is encapsulated with several laminated layers. One mm long and .7 mm in diameter (Quilliam, 1966), it filters low freqency. In its functional range, it is single impulse or maximally sensitive to vibrations from 300 to 400 Hz., and is insensitive at frequencies of less than 100 Hz. (Mountcastle, et al., 1967). The highest density of the Pacinian corpuscle is in the fingertips (Iggo, 1977).

Hair Follicle Receptors

Hair follicle receptors respond to light touch and to hair bending with a frequency of discharge proportional to hair displacement.

Sensitivity of hair follicle receptors ranges from several hairs distally to several centimeters proximally.

Slowly Adapting Mechanoreceptors

(provide continuous information concerning the state of the skin)

Merkel Discs

Merkel discs respond to skin deformation and maintain the discharge rate during deformation. The range of the Merkel disc involves the relation between the extent of skin deformation and disc firing rate; the rate follows a power function in relation to deformation.

Ruffini Endings

Ruffini endings provide redundant information; they discharge at a steady rate that is proportional to skin displacement.

Glaborous Skin Mechanoreceptors

(Meissner Corpuscle)

The Meissner corpuscle is located in the non-hairy skin, primarily in the hand and the palm. These receptors are more differentiated and highly organized than the mechanoreceptors in other areas. They are rapidly adapting receptors sensitive to skin shear and deformation, distributed in the dermal papillae.

Mechanoreceptors are functionally sensitive to changes in temperature. They are maximally sensitive at skin temperature of 30 to 40 degrees centigrade, and experience degradation of performance with temperature variations outside this range.

Thermoreceptors

Thermoreceptors are sensitive to small changes in local skin temperature, i.e., hot and cold spots. Their precise morphology is unknown, but their sensitivity ranges have been defined:

Cold Receptors	15-35 degrees centigrade
Warm Receptors	35-45 degrees centigrade
Normal Skin Temperature	33 degrees centigrade

(Iggo, 1977; Zotterman, 1976)

Nocioreceptors

Nocioreceptors are responsive to intense mechanical or thermal stimuli that are potentially or actually tissue damaging. Again, the receptors are differentiated by the stimuli to which they are sensitive:

Mechanical Nocioreceptors

Mechanical nocioreceptors have unmylinated or small diameter axons. They have distribution in the human skin; their range is a function of individual sensitivity.

Thermo Nocioreceptors

Thermo nocioreceptors (Iggo, 1959) have unmylinated axons. Their range of sensitivity induces activity at more than 42 degrees centigrade or less than 10 degrees centigrade.

In applications of control for remote manipulation, there has been little use made of the large range of tactile sensitivity in the human operator. Sensors have been developed to provide automatic control of robotic systems; however, there have been few, if any, driving forces to develop displays to provide the human operator with information of sufficient density and differentiation to be useful in manual control.

A wide ranging survey of touch sensing technology was conducted recently by Harmon (1980). Since his study was concentrated exclusively on tactile sensors, it covers the area to greater depth than we could hope to accomplish. Harmon comments on the level of sensor technology:

> The state of the art in tactile sensing is surprisingly primitive. Up until the last few years, touch feedback systems for robots and manipulators were very simple and relatively crude. The industrial systems still employ primitive devices; most of the more sophisticated and complex tactile sensors are in laboratory development, largely in academic or government settings and seldom in industrial use.
>
> Harmon, 1980

Various sensors have been developed in laboratories and industry to detect contact, proximity and pressure. The main criteria when choosing sensors for an advanced manipulator system are the capacity to be placed in high density arrays, and the potential for being adapted to task environments. While touch sensors typically require physical contact between sensor and the object in the environment, tactile information can also be acquired by non-contact means. Contact sensors include microswitches, strain gauges and pressure sensitive materials. Among the proximity sensors are inductive and capacitive transducers, optical devices and imaging systems.

Industrial Sensors

Microswitches and pneumatic jets, though crude, are in current use (Harmon, 1980). Switches made of conducting rubber and metal are used in the HI-T-HAND robot by Hitachi (Harmon, 1980). Cincinnati Milacron also uses microswitches in its robots.

If strain gauges can be configured properly, they can sense high density tactile information. Certain strain gauges available from Celesco Transducer Products, Inc., are as small as 0.2032 cm X 0.01524 cm X 0.00127 cm (0.080" X 0.006" X 0.0005"). Whether strain gauges can operate in a hostile environment without failure must be determined. Binford (1973) found breakage and insufficient resolution problems when he assessed semiconductor strain gauges as touch sensors. The Celesco strain gauges are only one-fifth the length of those tested by Binford.

The most promising sensors for touch information are pressure sensitive materials. Some of these materials have the potential to be placed over a manipulator in the form of "artificial skin." Conductive elastomers with differing characteristics have been offered commercially by Dynacon Industries. All types (Dynacon A, B, C) are constructed of silicon rubber impregnated with metallic compounds. Dynacon A is the most sensitive, highly conductive, and is susceptible to noise, conductivity drift and saturation at low pressure (Snyder and St. Clair, 1978). Dynacon B is designed for use as a switching device. Dynacon C is constructed so that its resistance varies exponentially with the inverse of the applied pressure. It is subject to hysteresis, and is not as sensitive as the type A. Company literature claims a resolution of 50 points per square inch. The major drawback of Dynacon is that it tends to fatigue rapidly, becoming useless after a few hundred applications of pressure. Crushing by sharp objects often cuts the material, and cracks develop; this does not result in catastrophic failure, but in rapid decrease in the material's sensitivity. Harmon (1980) reports that Dynacon D is under development.

This material is intended to be tougher, more linear, and less subject to hysteresis. The matter of Dynacon development may be moot, however, as Dynacon Industries appears to have recently gone out of business. Japan Rubber, Incorporated, with offices in New York City, manufactures similar materials.

Harmon (1980) mentions another pressure sensitive material called "Pressistor," which is manufactured by Innovation Labs. Pressistor is painted onto porous materials or electrode arrays, and thus can take any shape. Presistor materials are described as "piezo-resistive semiconductor powders in organic polymers." The thickness of the material controls its sensitivity. It is very stable and capable of high speed (10^{-9} seconds) switching due to avalanching in some configurations. Pressistor materials can also be configured to have a good range of force/resistance characteristics, though hysteresis is still a problem. The "500 Series" under development is supposed to have low hysteresis and stable operation up to 1100° Farenheit.

Inductive and capacitive transducers are available for industry, but their size makes the current state of the art proximity devices unlikely choices as touch sensors. For example, inductive transducers from IVO Industries, Inc., have a minimum sensing surface diameter of 34 mm (1.36"). Under ideal conditions, these sensors can detect changes in distances of 10 millionths of an inch (Michelson, L., Lion Precision Corporation). Inductive proximity switches have found use in Cincinnati Milacron robots, but also impose restrictive size limitations for an anthropomorphic model.

Optical devices can measure sensor-object distances; with sufficient resolution, this could provide tactile information. Optoelectronics, Inc. supplies lead sulfide, lead selenide and pyroelectric sensors that are sensitive to different ranges of infrared radiation. These sensors are available in high density arrays. Usefulness of these sensors is limited by the availability of touch information through infrared radiation in the task environment, and by the difficulty of configuring the sensors on a manipulator arm.

Skan-A-Matic Corporation manufactures optical sensors with self contained LED light sources. The light sources are remoted from sensor and target surface by optical fibers. The light reflected from the target is recorded by a photosensitive element in the tip of the sensor. At a distance from target material of 0.100 inches, resolution of 0.010 inches is possible (0.254 cm and 0.0254 cm, respectively). The sensor described has an 0.250 inch (0.635 cm) diameter active surface, so it is too bulky for high density arrays. The sensor itself, however, may be remotable from the manipulator by further application of fiber optics; the virtual density of the sensor array might then be determined by the minimum diameter of the optical fibers leading from the manipulator to the Skan-A-Matic sensors. The feasibility of using optical fibers as a "two-way street for light" to take remote measurements has been demonstrated at Lawrence Livermore Laboratory (Miller, 1980).

Laboratory Sensors

Tactile sensors for teleoperator control have been used at Stanford Research Institute (Hill and Bliss, 1971a,b; Bliss, et al., 1971). This system incorporated switches made of metal contacts and conducting rubber. When sufficient pressure was applied to the rubber, it made contact with the metal, the circuit was closed, and the manipulator was known to be touching some surface. The highest density of sensors was on the inner "finger" surfaces of the tongs of a mechanical hand, a 6 X 24 array of 144 contacts in an area of 10 X 50 mm.

Many of the experimental sensors designed to extract tactile information from the environment have been developed at the Advanced Teleoperator Laboratory at the Jet Propulsion Laboratory. These include proximity, pressure and slip sensors (Bejczy 1980 a,b; Bejczy and Brooks, 1980). The size of the proximity sensors is such that they cannot truly be considered as touch sensors for teleoperator operation; however, both light source and detector are remoted from the end-effector by fiber optic cables, as discussed for the Skan-A-Matic sensors mentioned earlier in this report. The ability of the JPL sensors to measure distances is dependent on knowledge of reflectivity conditions.

The contact sensors developed are multi-point proportional. The smallest configuration fits a 4 X 8 array of sensitive elements into a 12 X 24 mm rectangle. Pressure can be measured over the range of

2 to 50 N/m^2. The sensors consist of pressure sensitive conducting plastic placed over a set of electrodes. Changing the pressure on the plastic changes its conductivity. Current flow can be used to measure pressure on the sensor surface.

One type of JPL slip sensor identifies not only the simple occurrence of slip, but also its direction. This sensor relies on a small (~1.27 cm or .5 inch) dimpled sphere supported on a bearing. Any slippage of a surface touching the sphere causes the sphere to rotate. A needle, rising from a conductive plate, touches the sphere on the opposite side; the movement of the sphere causes the needle to oscillate, thus shifting the conducting plate, which then touches an appropriate electrical contact. The present design, with 16 contacts, can identify slip in 16 directions. It is too large for tactile arrays, but in principle much smaller versions could be constructed.

Slip sensors developed by others have relied on piezo-electric crystals (Harmon, 1980) and stylus contact with the surface.

High resolution optical sensors are used on the "fingers" of an end effector by Leifer at Stanford University (Leifer, et al., 1980). These sensors provide touch information and operate over a range of 1 to 4 mm. They are based on the Hewlett-Packard HED-1000, which is used commercially for reading bar-codes.

An experimental, touch-sensitive material described as "artificial skin" was developed and used with the Belgrade hand (Stojiljkovic and Clot, 1977; Clot, et al., 1975). The material detects both pressure and slip. In designing this "skin," the experimenters were clearly attempting to duplicate some of the properties of natural skin; the result is that the sensors are subject to adaptation and sensory inhibition, just as are analogous biological systems. The skin consists of a surface conducting layer separated from a layer of electrodes by an elastomer. A voltage potential is applied to the surface layer; deformation of the material changes the resistance between surface and electrodes. No description of sensor densities is reported, but the approach of creating an artificial integrated touch organ seems promising.

One potential limitation of elastomer-based "artificial skins" should be mentioned: Elastomers are extremely sensitive to at least some hostile environments. Recently researchers at Oakridge National Laboratory planned to use tactile sensors for remote manipulation of nuclear materials. The sensors were from the Advanced Teleoperator Laboratory at JPL. The attempt to use touch sensors was abandoned when it was discovered that the elastomer quickly broke down in the high radiation environment of the manipulator tasks (Personal Communication). This is only an isolated case, but it is possible that as mechanical analogs of biological systems are developed, they will be prone to failure in the same situations as their living counterparts. And since, for the foreseeable future, we will not have self-repairing materials, these artificial systems may not function effectively except in highly specified environments.

Displays

Display Approaches

Of significantly greater difficulty than acquiring tactile information is displaying it to the human operator. To achieve presence, touch information should be displayed through channels most natural to the operator, that is, if the manipulator holds an object, the operator should feel that object in his own hand. There has been even less effort to develop tactile display technology than to develop the corresponding sensor technology. Tactile sensors can supply information directly from the environment to robots, teleoperators and prosthetics; if the data must be displayed to a human being, visual or auditory displays normally suffice. But tactile displays, as such, are irrelevant to robots; tactile displays have been applied to humans only when other sensory modalities are unavailable. As a result, almost all touch displays developed so far have been used in laboratory experimentation; the few commercially available displays that exist are primarily designed as aids to the blind.

Tactile stimulation, based both on mechanical and electrical principles, has been attempted. These displays have most often been used in studies of ways to partially compensate for damaged senses and/or lost limbs. This can be primarily classified as optical-to-tactile image conversion for the blind, or touch feedback for limb prostheses and orthoses. Some researchers have attempted to assess the applicability of touch displays for reducing the information load on the visual modality in aircraft guidance and control. In at least one instance, tactile feedback was incorporated into an experimental remote manipulation system (Hill and Bliss, 1971 a,b).

Mechanical Stimulators

Almost every attempt to produce tactile sensations has been via vibrotactile stimulators. The pressure or current presented is not constant, but is pulsed; depending on choice and the capacity of the particular stimulator, the pulse frequency may vary from a few per second up to hundreds of pulses per second.

The mechanical means of producing tactile stimulation include airjet, piezoelectric, electromagnetic and electro-mechanical stimulators.

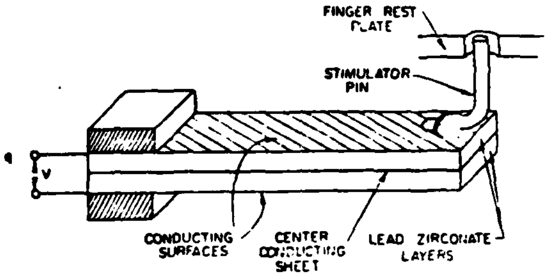
Airjets, as the name implies, depend on pulses of air pressure against the skin, rather than physical contact with some solid object. Air is alternately forced through an exhaust tube or a tube that feeds into the tactile display; the flow is directed by a valve, usually electromagnetic (conceptually similar to the electromagnetic stimulator described later in this report). In a sense, airjets are "remote" stimulators, in that they can be positioned some small distance from the surface of the skin, and may therefore be less restrictive to the user. Since the space around an operator's hands, for example, is likely to be at a premium, the use of stimulators which can be closely packed as the outer diameters of the air tubes might be advantageous. Airjets, however, are limited by the difficulties of creating a controllable air stream of minimal diameter and sufficient pressure to produce sensation, while maintaining reasonable power requirements.

Airjet stimulators have been evaluated and compared to visual displays in tracking tasks by Bliss (1966, 1967), Seely and Bliss (1966) and Hill (1970). A sample set of parameters for the stimulators used by Hill are: 1 psi pulses, as measured one-eighth inch (0.3175 cm) directly in front of the airjet outlet; 160 pulses per second; 1.5 millisecond pulse width and .5 millisecond rise time. These parameters are for an air tube of 0.031 inch (0.07874 cm) in diameter. Airjets are most suited to pulse rates of 200 pps or less, as they do not operate reliably at higher frequencies. This limitation seems, however, to be mostly an artifact of the high-speed valve controlling the air flow, and may not be true in general.

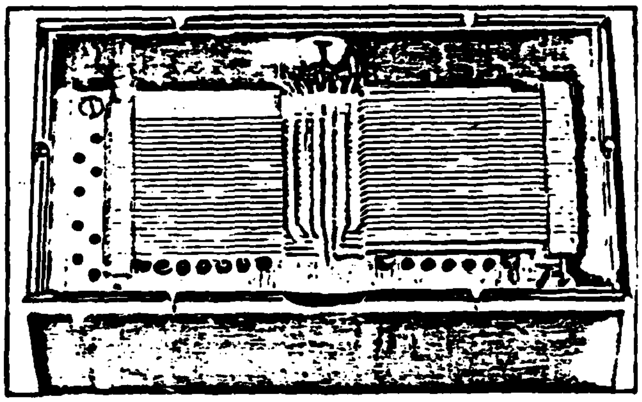
When airjets were incorporated into optical-to-tactile reading machines, blind subjects found them more comfortable than the "tickle" of piezoelectric bimorphs (Bliss and Crane, 1965). Hill and Bliss (1971 a,b) combined airjets and bimorphs into a tactile display for a teleoperator system; their use improved performance with a supervisory control system. There was no detailed report of the sensations induced.

Piezoelectric bimorphs were another often used mode of tactile stimulation in the work of J. C. Bliss (Hill and Bliss, 1971 a,b; Bliss, et al., 1970; Bliss, et al., 1971). The bimorphs were constructed of two oppositely polarized layers of lead zirconate, bonded to a center conducting sheet, all sandwiched between two more conducting surfaces (of nickel). When a voltage is applied across these layers, the sandwich deflects, approximately 0.04 mils per volt. By rapidly reversing the voltage polarity, vibration is induced. One end of the unit is mounted and a pin is attached to the free end, as shown in Figure 1. Bimorphs of this type have definite resonance properties; for the particular bimorph used, the resonant frequency was about 200 Hz. If another pulse frequency were desired, the possibly difficult task of designing a new bimorph with the appropriate resonant frequency would be necessary. Rogers (1970) has suggested that, at least for tactile reading situations, the 200 Hz frequency is nearly optimal.

Using the bimorphs described above, tactile displays of 144 pins have been constructed to stimulate a single fingertip. The pins were placed in a 6 X 24 array covering an area of one and one eighth by one-half inches (2.8575 X 1.27 cm). Even though each bimorph may be over an inch (2.54 cm) long, only the attached pin makes contact with the



a) Piezoelectric bimorph reed mounted for use as a tactile stimulator.



b) Tactile Stimulation Array The 24-by-6 array of tactile stimulators fits on one fingertip. The stimulator pins are spaced 50 mils apart along the finger and 90 mils apart across the finger. The perforated surface is curved to fit the finger.

FIGURE 1 PIEZOELECTRIC BIMORPH STIMULATORS

from: Bliss, J. C., M. H. Katcher, C. H. Rogers, and R. P. Shepard, "Optical to Tactile Image Conversion for the Blind," IEEE Transactions on Man-Machine Systems, MMS-11(1):60-61, March, 1970 skin; the shape and structure of the bimorphs allow them to be cantilevered, one set above another, such that a relatively dense display array can be built. For example, each bimorph affects a skin area of about 1 millimeter in diameter. This compares favorably with airjets used by the same experimenters (Hill and Bliss, 1971a), which stimulated an area about five millimeters in diameter. Large arrays of high density piezoelectric stimulators would probably not be feasible because of the space requirements for the mechanisms to support each pin.

Electromagnetic plunger stimulators have been constructed and applied to the thumb (Ballard and Hessinger, 1954) and to the back (Holmlund and Collins, 1970). The basic design of the stimulator used in the latter case is shown in Figure 2. It was described as a "magnetically suspended polarized solenoid" stimulator. The stimulator has basically two components: the plunger, which contains a permanent magnet, and a coil wound over a steel tube. Alternating the current through the coil causes the plunger to plunge, and then to retract. As with the piezoelectric bimorph, the plunger assembly has a resonant frequency. This frequency can be changed by altering (1) the magnet assembly mass, (2) the magnet strength, or (3) the driving coil current. The advantage over other vibrating displays is the capacity of this stimulator to maintain relatively constant power output to the skin, even when the skin-to-stimulator distance is variable. The power was judged nearly constant for distance changes of about one centimeter.

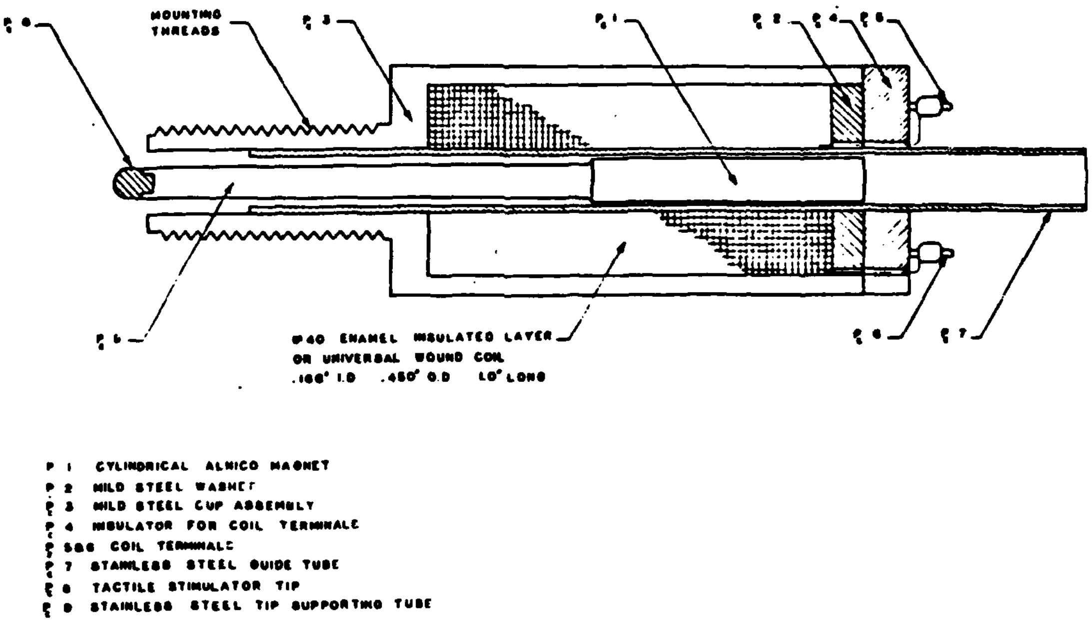


FIGURE 2 CROSS-SECTIONAL DRAWING OF TACTILE STIMULATOR WITH PERMANENT MAGNET PLUNGER IN RESTING POSITION

from: G. W. Holmlund and C. C. Collins, "An Electromagnetic Tactile Stimulator," The Journal of Biomedical Systems 1(3):28, 1970

Holmlund and Collins (1970) were able to achieve a spatial resolution of one centimeter on the skin of the back using these stimulators with a plunger tip diameter of 0.5 millimeters. A 20 X 20 array of stimulators with 1 mm diameter teflon tips was the display in a "tactile television" for the blind. In subsequent research, Collins (Collins and Saunders, 1970; Saunders and Collins, 1971) has apparently abandoned this type of stimulator in favor of electrocutaneous means.

Vibrotactile transducers have been constructed from the driving units of conventional loudspeakers (Hill, 1970). Another approach, one of the few not employing vibration, has been to include servo-controlled moveable segments in a handgrip (Sun, et al., 1979).

Electrotactile Displays

Any of the touch sensations -- pressure, pain, heat -- can be stimulated electrocutaneously (Geldard, 1972). Most electrotactile stimulation has been done with the intention of evoking touch or pressure while avoiding pain. For the past decade, this type of display has been generally preferred to the various mechanical methods of tactile stimulation; for most applications, it is the most convenient. Pulse width and frequency both can be easily modified without changing the stimulators themselves. Except for the fingers, the power requirements for electrical stimulation are usually less than those for mechanical stimulation of the same skin surface (Collins, 1970). Present portability and potential for miniaturization are further advantages in many circumstances. Thus, despite the fact that electrotactile displays are the most artificial[1] described so far, they have gained an undeniable popularity. This type of display seems to be the best choice for tactile display in the advanced manipulator system.

Electrocutaneous stimulation is evoked after placing some configuration of electrodes in contact with the skin. An electrical pulse train, usually with one of the parameters of current, voltage or power held constant, is passed through the skin. The possible variations of the remaining parameters are many, and provide the means of controlling the tactile sensation. Pulses can be modulated by frequency and amplitude; changes in pulse shape and width can convey information. The basic pulse train itself can be bipolar or monopolar. The number and physical arrangement of electrodes will also affect sensations (Szeto, 1977).

The implementation of electrotactile stimulation is not without difficulty. A system which relies on the skin as an element in an electrical circuit presents unique problems. Depending on the moistness of the

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[1] "Artificial" can be defined in terms of deviation from conventional causes of tactile sensation. In a usual environment (as opposed to a specified task environment), such sensation is induced by physical contact between the skin and some object. Use of any of the mechanical stimulators described above is simply a special case of physical contact. In the case of electrotactile stimulation, there is physical contact with one or more electrodes, but this is not the primary source of sensation.

skin, its electrical resistance can vary significantly. Polarization can occur: current flow in one direction through the skin is partially blocked. As a result, the sensations from current flow in each direction may differ. If spontaneous local breakdown of the skin takes place, regions of high current density will be generated, leading to pain, reddening of the skin and blisters. The choice of type of pulse (bipolar or monopolar) and the pulse frequency can allow skin adaptation to occur; an individual's sensitivity to changes in signal will be reduced. High stimulus intensities are, of course, painful.

To a useful extent, many of these problems have been solved. Massaging the skin with electrode lotions or applying electrode pastes can minimize skin resistance changes, which may otherwise vary over a factor of a thousand. Collins (1970) has suggested capacitive coupling to the skin to prevent polarization. Constant current stimulation and narrow pulses (300 microseconds or less) can be used to help avoid local breakdown (Szeto, 1977).

Electrode positioning is important in avoiding pain and controlling resolution of the intended sensations. In certain areas of the body surface, such as the abdomen, electrode placement can be basically arbitrary. But for skin surfaces most likely to be of interest in remote manipulation (the hands, arms, feet and legs), this is not the case (Solomonow, et al., 1976). Electrode translations of as little as one-half inch (1.27 cm) can alter the sensation produced by a constant stimulus from acceptable to painful. If an electrode stimulates motor fibers, it can cause motion at some distance from the stimulation site; localizing the stimulation to the electrode is then difficult. Thus, the skin surface to be stimulated must be mapped and appropriate sites chosen before the display system can be implemented.

To close a single circuit through the skin, there must be two electrodes in contact with it. In a concentric electrode, one electrode is surrounded by the other, separated by an annular ring of insulating material. In a multi-electrode display, if the concentric electrodes do not share a common ground, the current does not tend to penetrate deeply into the subcutaneous tissues. The sensations produced are relatively localized, and the pain associated with deep current penetration is less likely. Another electrode configuration involves an "active" electrode at the stimulation site and a "return" electrode located at some other position on the body. Even if multiple stimulators are used, only one return electrode is required. In this configuration, the current flows laterally over much greater distances, and extends deep into the tissues; the resolution of the sensation is reduced over that of a concentric electrode system. In general, concentric electrode displays are preferred.

Electrotactile stimulation has been studied as a replacement for mechanical stimulation in "tactile television" (Collins and Saunders, 1970; Saunders and Collins, 1971; Collins, 1970). Strong and Troxel (1970) have investigated a hand explorable display, which seems to evoke sensations with many of the properties of texture. An important factor determining the information handling capacity of the electrocutaneous communications channel is the minimum distance between two electrodes such that stimulations from the electrodes are perceived as distinct from each other. This is called the two-point discrimination threshold. This has been studied as a function of pulse frequency, stimulation location, side of body, and stimulation code (Solomonow, et al., 1977); as a function of frequency, pulse width and pulse time delay (Solomonow, et al., 1978), and as a function of learning (Solomonow, et al., 1979). Optimization of similar parameters for use of electrotactile feedback in prostheses and orthoses has been the subject of work by Szeto (1977).

Manipulators: Structure and Configuration

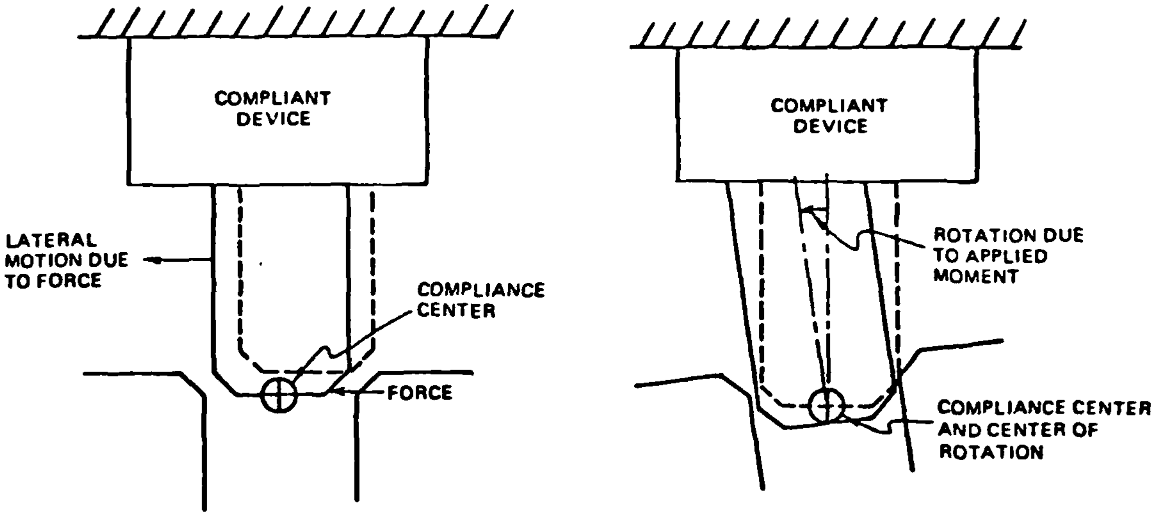
Since master-slave teleoperators have existed for about 30 years, basic position control has long been commercially available. While these systems have not been strictly anthropomorphic, there are no major technical reasons why this property could not be achieved. Vim Systems, Inc., offers a master-slave manipulator with three degreees of freedom in the "shoulder," one degree in the "elbow," and three degrees in the "wrist." The Central Research Laboratories division of Sargent Industries sells about 15 models of master-slave systems, some with seven degrees of freedom. All but one, however, incorporate direct mechanical linkages between master and slave, thus precluding any significant remoting of the operator from the task. Their one bilateral model with electrical linkages has a five foot reach, and a 50 pound hand grip capacity; it was designed ten years ago for use at Fermi Lab, and there are only a few units in existence. Oakridge National Laboratory is acquiring this model for its research into improving performance in manipulation of nuclear materials. This manipulator has not been significantly modified in the past decade, yet it represents the state of the art in commercially available electric-servo master-slave manipulators. The unit is not normally operated in an anthropomorphic configuration; but if it were literally turned upside-down, and the limb lengths were adjusted, this manipulator would closely approximate the movements of a human arm. The end-effector in the existing system is a simple vise grip; it would have to be replaced with an articulated hand for fine position control.

An anthropomorphic master-slave manipulator known as the NASA/Ames arm was designed and patented in the mid-1970's (Vykukal, et al., 1977). This uniquely structured arm is now resident at the Jet Propulsion Laboratory Advanced Teleoperator Laboratory (Bejczy, 1980b). As opposed to most commercial master-slave manipulators, in which the operator merely grips a handle at the end of the master arm, the operator of the NASA/Ames device has his arm encased in an exoskeletal structure. Any single joint motion by the operator is resolved as the rotation in opposite directions of two contiguous sections of the master exoskeleton. The same motions are duplicated in the electrically linked slave arm. This is the most truly anthropomorphic master/slave manipulator system we have encountered; elements of its structure can be found in the conceptual design section of this report.

"Slave" arms are of course available from the robotics industry, though a master control arm and control algorithms would still have to be developed to complete the position subsystem of an advanced manipulator system. Under computer control, robot arms can achieve high position precision and repeatability. End effectors are either special purpose or simple vise grips. There is no requirement in the industry for robots to be particularly anthropomorphic. Goodrich (1980) reviews some industrial robot capabilities. Robot arms usually rely on electric servos for light weight applications, hydraulics for heavy loads. The Unimation PUMA, which has a basically anthropomorphic design, can have a repeatability of ±0.004 inches (0.01016 cm) while handling loads up to five pounds. Other sophisticated robots, designed to carry several tons, may have a repeatability of ±0.05 inches (0.127 cm). In other manufacturing applications, robot systems have achieved position accuracies up to ±0.0001 inch (0.000254 cm); a "tweezer gripper" device checks part size tolerances to ±0.005 inches (0.0127 cm).

General purpose, human operated advanced manipulator systems, in contrast with computer controlled systems, cannot be expected to achieve equivalent position accuracies.

In the context of assembly, there has been an approach which makes use of lack of precision or compliance rather than rigid precision for endpoint placement. Seltzer (1979) and Drake, et al. (1977) have explored techniques for compliant positioning of parts for robot assembly. The approach incorporates an end effector assembly with a mobile mount in the area of the wrist. The mobile mount allows a self correcting feedback to align the part held by the hand to the insertion requirements (Figure 3). In addition to the compliance for assembly, a more recent advance (Seltzer, 1979) includes instrumentation of the compliant wrist. Instrumentation allows the device to be used in measurement. For our purposes, the wrist becomes another form of tactile sensor. The instrumentation procedure uses optical links for the measurement of displacement of the endpoint. There are photosensitive elements mounted at the center of the device, and a shutter is mounted on the compliant end controller. The shutter moves between the LED light source and the photosensitive array. Relative shading by the shutter indicates amount and direction of movement of the compliant endpoint. The photosensitive array is produced by Reticon Company, and has a density of 256 elements on a 25 micron surface. The range of sensitivity is determined by the compliant range of the end effector, e.g., .5 cm to .6 m.



a) Response to Lateral Force b) Response to Lateral Moment

FIGURE 3 REMOTE CENTER COMPLIANT WRIST

from: Drake, S. H., P. C. Watson and S. N. Simunovie, "High Speed Robot Assembly of Precision Parts Using Compliance Instead of Sensory Feedback," Proceedings of the Seventh Annual Conference on Industrial Robotics, p. 94, 1977

CONCEPTUAL DESIGN

This conceptual design incorporates our assessment of the use of present technology to realize an advanced manipulator system, and our approach for demonstrating that system.

We stress that the proposed design is a conceptual feasibility study; it is not intended to be exclusive or optimal. It is intended to demonstrate the principle of transparency for an advanced manipulator system, in a laboratory setting. As with any design of a complex system, there are inherent tradeoffs and difficulties. We have made suggestions for surmounting the anticipated difficulties that we feel will expedite prototype construction.

System Overview

Figure 4 illustrates the total system design configured as a master/slave manipulator with integrated force and position control. Included are position, force derivative, tactile and thermal feedback.

The master/slave anthropomorphic design was adopted to facilitate feedback to the human operator with a minimal data processing requirement. It is not a necessary condition. Software transformation of any position related control to a kinematic analog

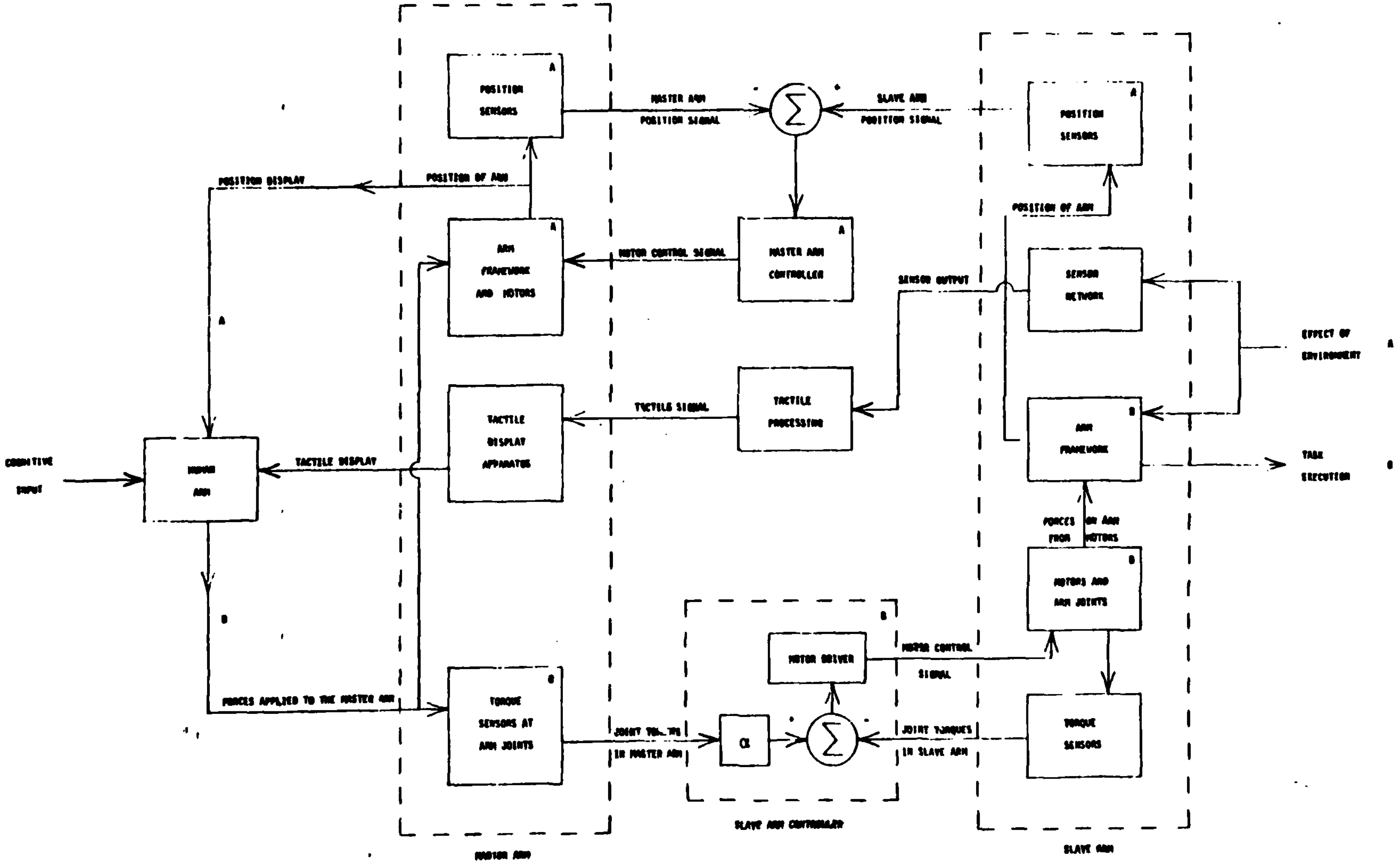


FIGURE 4 TELEPRESENT MASTER/SLAVE MANIPULATOR
(see Footnote, page 50)

Footnote to Figure 4

The slave arm controller shown is the simplest possible controller.

$$\alpha = \frac{\text{the force exerted by the slave arm}}{\text{the force exerted by the master arm}}$$

A feedback loop exists between the human operator and the slave arm. Forces on the master arm and the slave arm due to gravity could act as extraneous inputs to this feedback loop. These forces could be compensated for in the controllers of the master arm and slave arm, respectively, but only at the expense of introducing a delay into the feedback loop.

The need to compensate for graviational forces can be eliminated if the system is designed and used in such a way that extraneous inputs due to gravity at the master arm cancel the extraneous inputs at the slave arm. Two criteria must be met to accomplish this cancellation. One criterion is that, when in use, the master arm and slave arm must have the same orientation to their respective gravitational fields. The second is that each segment of the slave arm must have a center of gravity in the same location as the corresponding segment of the master arm and must have a weight that is proportional to the weight of the corresponding segment of the master arm. The constant of proportionality here must be equal to the ratio of the force exerted by the slave arm to the force exerted by the operator of the master arm. This ratio is the same as "α" in the formula and in the block diagram.

of the operator's position would serve the same purpose (Bejczy and Salisbury, 1980). Any controller that takes a control motion from the operator and translates to a similar motion in the remote manipulator would be likely to be a good controller.

The specific translation requirements are not known. It is not yet specified to what extent and to what fidelity the operator of a remote system needs feedback to achieve a sense of presence. It is, as yet, also undetermined whether the feedback needs to be delivered in the same way it is in the natural setting, or if it can be delivered in a reduced form, e.g., force displayed only as resistance at the end point of the controller. We have chosen the most nearly anthropometric design for our system. Empirical investigation will determine if the system complexity can be reduced.

The system operates as a force controller with position following. The basic functional loops of the design are:

A. Position Feedback Loop

Loop "A," the position feedback loop, serves to maintain the operator's limb and hand in position until the arm and hand of the slave remote manipulator are directed to another position. The position feedback then reduces static resistance to the operator's motion, and allows him to move through the same trajectory as the slave limb.

B. Force Control Loop

Loop "B," the force control loop, transmits the operator's commands, sensed as torques at the master arm joints, through the slave arm motor drive. The resultant change of position is then fed back through the position controller of the master arm to movement of the operator's arm.

The system operates as a force controlled servo, rather than the standard position control. This design was implemented because of the concern for tight coupling of the operator to the slave. The force coupling provides the operator with a "sense of effort" throughout the intended motion. This "sense of effort" is not a strain to the operator (provided, of course, that the manipulator and control friction losses are kept to a minimum), but it does give the operator a feeling of being in constant contact with the manipulator. Further, the force controlled manipulator allows no deviation between the operator's arm position and the slave arm position. Standard position controls have some position inaccuracy, dependent on how tightly the system is coupled. In addition to the control loops, there are feedback loops from the slave to the operator to provide high density tactile information at the human operator's fingertips, distributed pressure or touch information throughout the human operator's arm, and force information through the proprioception of the human operator's control moves.

Now we will discuss the specific subsystems.

The master arm/hand and slave analog in Figure 5 shows an operator in a bilateral system. The exoskeleton is designed after the NASA-Ames arm. Rotation and translation to account for the human operator's movement are accomplished by the simultaneous rotation of the torsional joints proximal and distal to the intended joint movement. The human operator is fitted with the master system, which is suspended by a tether to offset the system's weight. The flexible tether also allows free shoulder girdle, neck and chest movement. These movements allow the human operator to feel disencumbered, and could be incorporated into a total robot system as torso position information. The slave arm and hand are positional analogs of the operator's arm and hand. A slight translation from slave full closure to operator partial closure of the hand is required to compensate for hand controller encumbrance.

Figure 6 shows the master arm with position control servo motors attached. Position information to the master arm is derived from position sensing potentiometers on the slave arm (see Figure 5). The movements available to the operator through coordinated torsional joint rotation are:

Shoulder	Abduction/adduction, elevation, azimuth and elevation
Elbow	Flexion, extension
Wrist	Flexion, extension and rotation
Forearm	Pronation and supination.

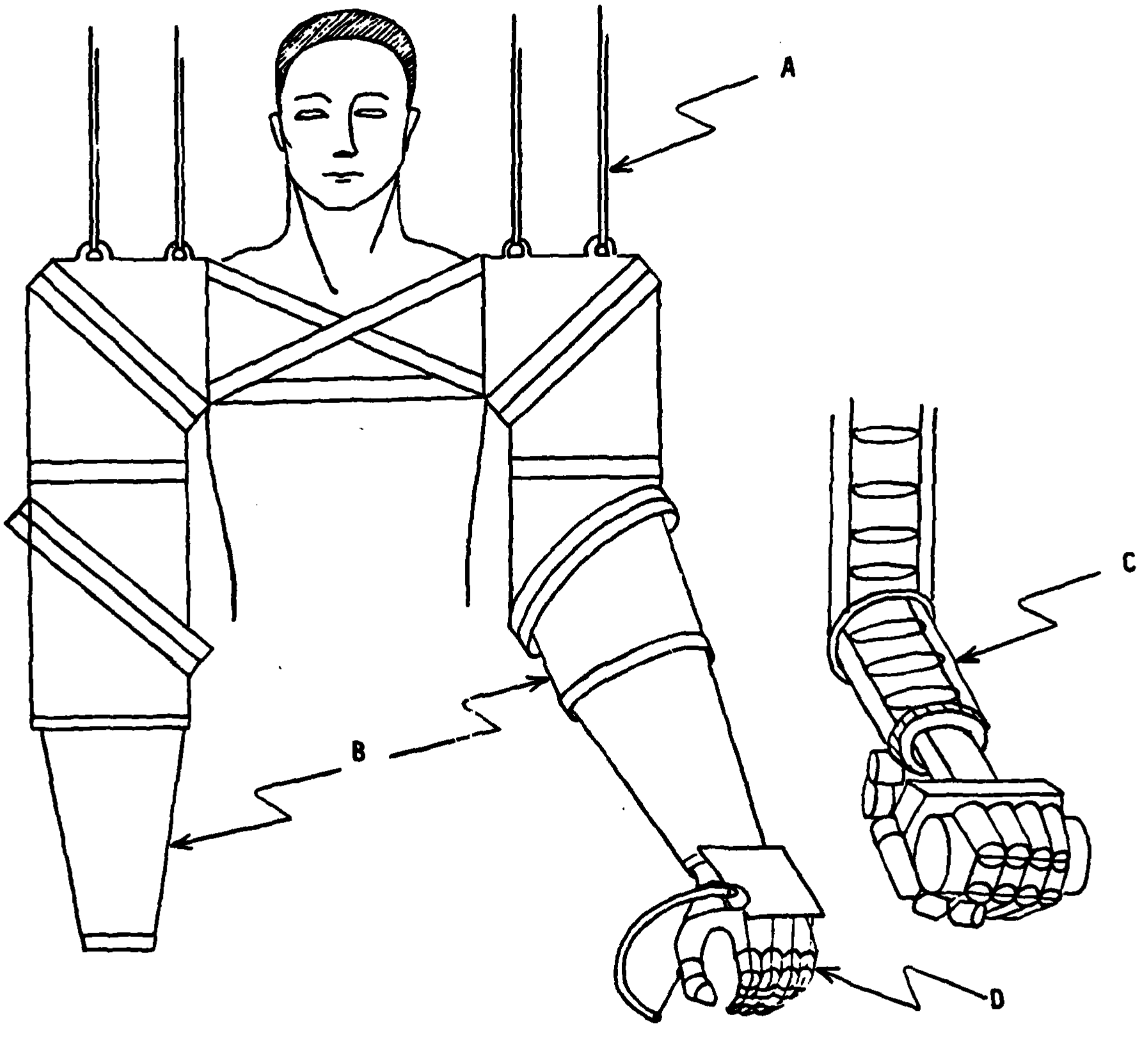


FIGURE 5 MASTER SLAVE SYSTEM CONCEPT

A) SUSPENDED SUPPORT TETHER

B) MASTER EXOSKELETON

C) SLAVE ARM AND HAND, KINEMATIC ANALOG TO MASTER ARM

D) MULTIARTICULATED MASTER HAND

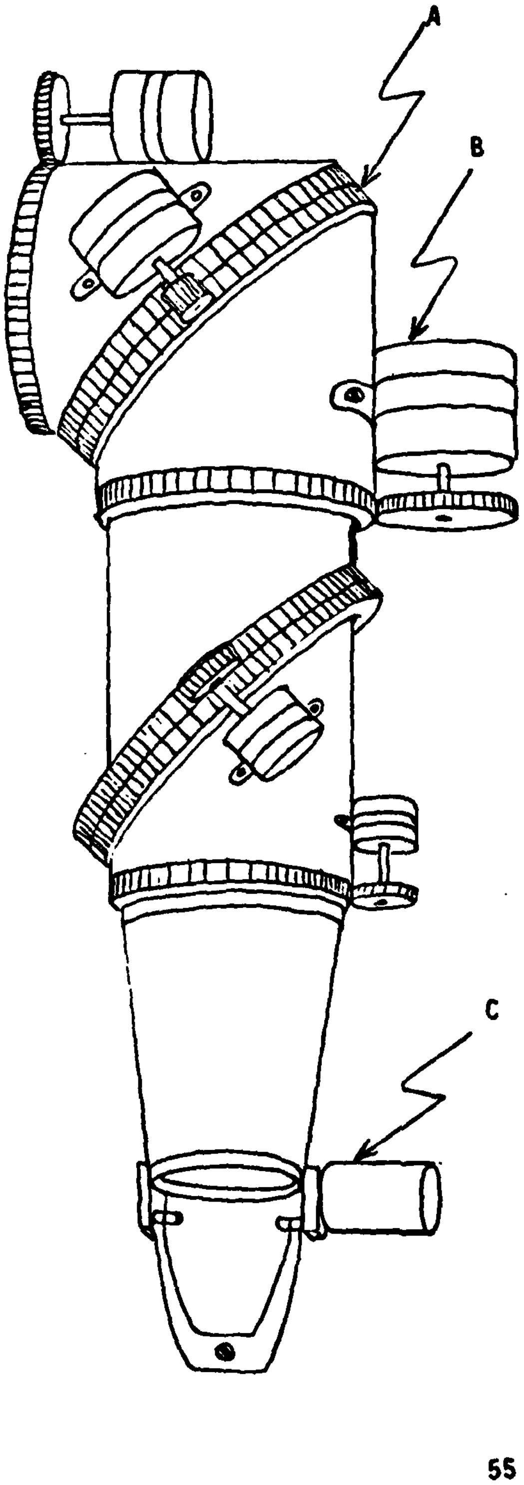


FIGURE 6   MASTER ARM

A) MASTER ARM TORSIONAL JOINT LINKAGE CONTAINING ROTARY POTENTIOMETER

B) SERVO MOTOR PROVIDING POSITION FEEDBACK

C) WRIST FLEXION-EXTENSION CONTROLLER

The master arm exoskeleton encloses a system to display local and distributed pressure, touch and temperature (Figure 7). The sheath is hydraulically activated with hot, cold and exhaust tubules. The palm is similarly stimulated in response to slave palm contact. The display sheath is stationary with respect to the operator's arm. The sensor sheath at the slave arm is isomorphic to the operator's display sheath. The stimulus at the slave "skin," therefore, is mapped to the same point on the operator's arm.

As noted previously, one of the most refractory areas of development in robotics is the articulated hand and corresponding controller. Figures 8, 9 and 10 demonstrate our design concept for a fully articulated and sensitive hand controller. The slave hand responsive to this controller is available as an expansion of the Electrotechnical Laboratory hand. The concept of the articulated controller is quite stable; it is similar to marionette control. The cable controllers (analogous to external tendons) are driven by servo motors mounted on the hand plate. Control and feedback are effected as can be seen in Figure 5.

The hand controller and display communicate fully articulated position and force commands independently for each finger. Figure 8 provides a side view concentrating on the control of prehension. The most basic component of skilled manipulation is the function of the

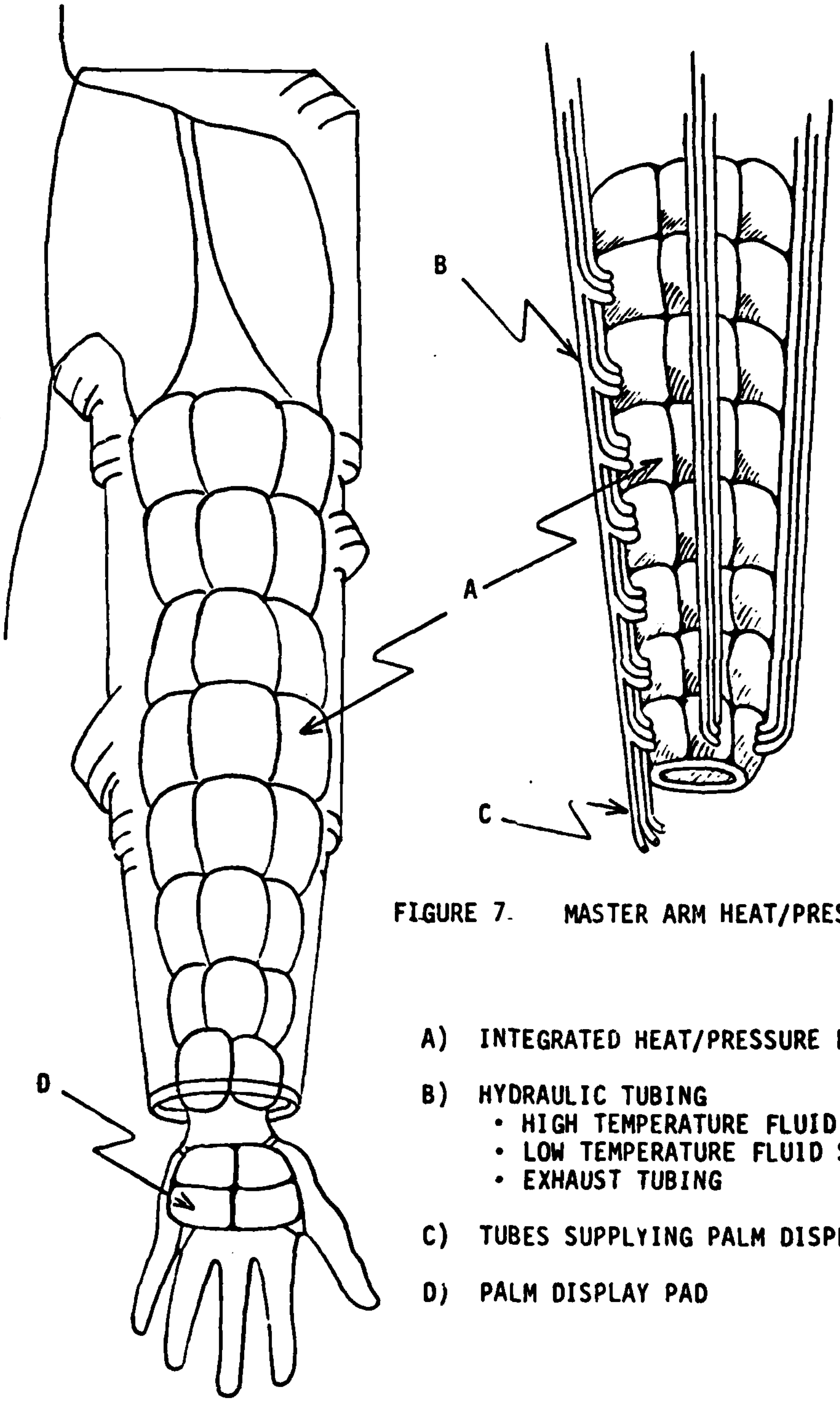


FIGURE 7. MASTER ARM HEAT/PRESSURE DISPLAY SLEEVE

A) INTEGRATED HEAT/PRESSURE DISPLAY POCKET

B) HYDRAULIC TUBING
  - HIGH TEMPERATURE FLUID SUPPLY
  - LOW TEMPERATURE FLUID SUPPLY
  - EXHAUST TUBING

C) TUBES SUPPLYING PALM DISPLAY

D) PALM DISPLAY PAD

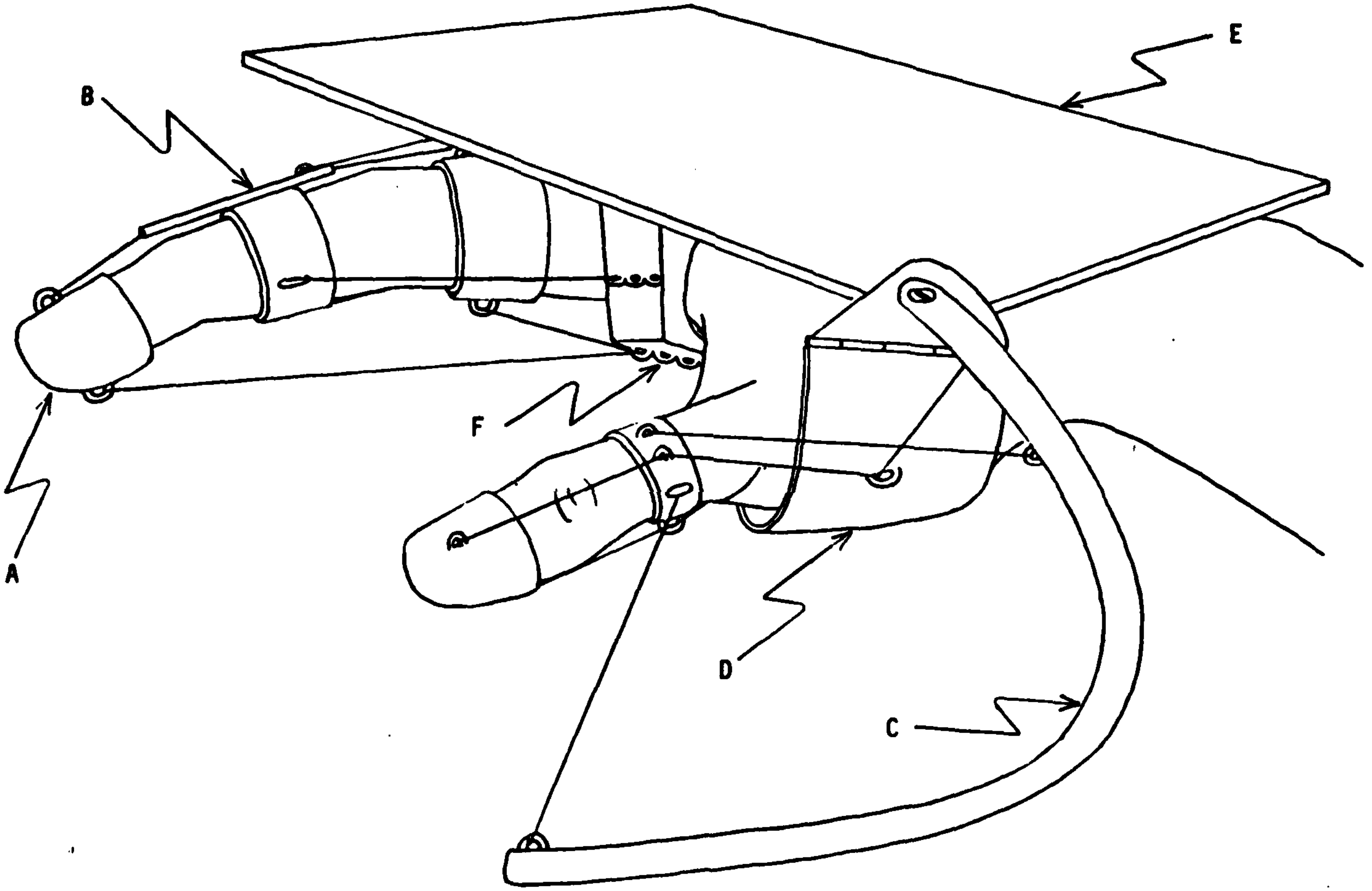


FIGURE 8 MASTER HAND CONTROLLER (SIDE VIEW)

A) FINGER THIMBLE DISTROL WITH ELECTROTACTILE DISPLAY
B) FINGER DISTROL RING WITH CABLE GUIDE
C) THUMB DISTROL OUTRIGGER TUBE
D) HINGED LOWER THUMB DISTROL
E) TORQUE MOTOR MOUNTING PLATE
(MOTORS AND CABLE POSITIONS NOT SHOWN)
F) KNUCKLE BRACE WITH EYELETS AND CABLE GUIDES

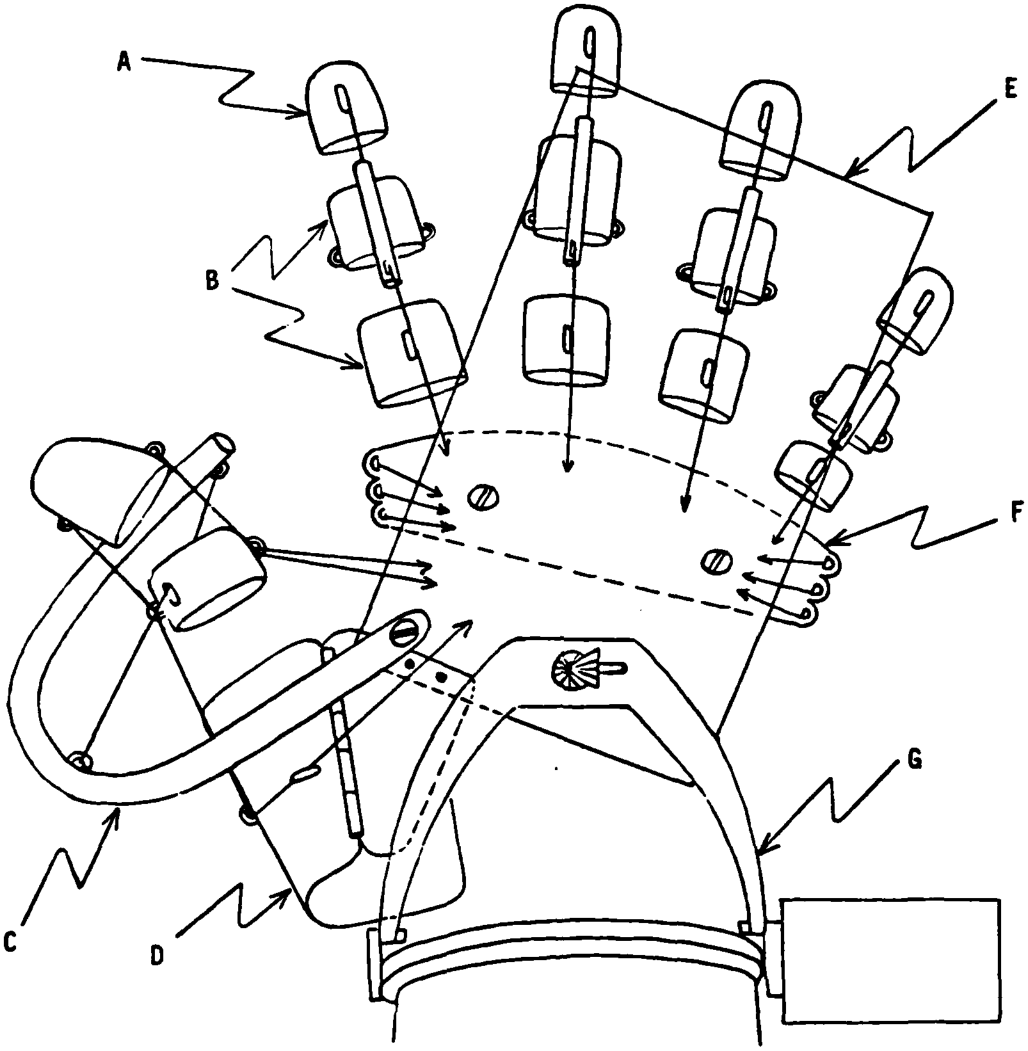


FIGURE 9 MULTIARTICULATED MASTER HAND (TOP VIEW)

A) FINGER THIMBLE AND ELECTROTACTILE DISPLAY
B) FINGER DISTROL RING
C) THUMB DISTROL OUTRIGGER TUBE
D) HINGED LOWER THUMB DISTROL
E) TORQUE MOTOR MOUNTING PLATE (MOTORS NOT SHOWN FOR CLARITY)
F) KNUCKLE BRACE
G) WRIST FLEXION-EXTENSION DISTROL

NOTE THAT COMPONENTS UNDER MOTOR PLATE ARE GENERALLY NOT DASHED FOR CLARITY.

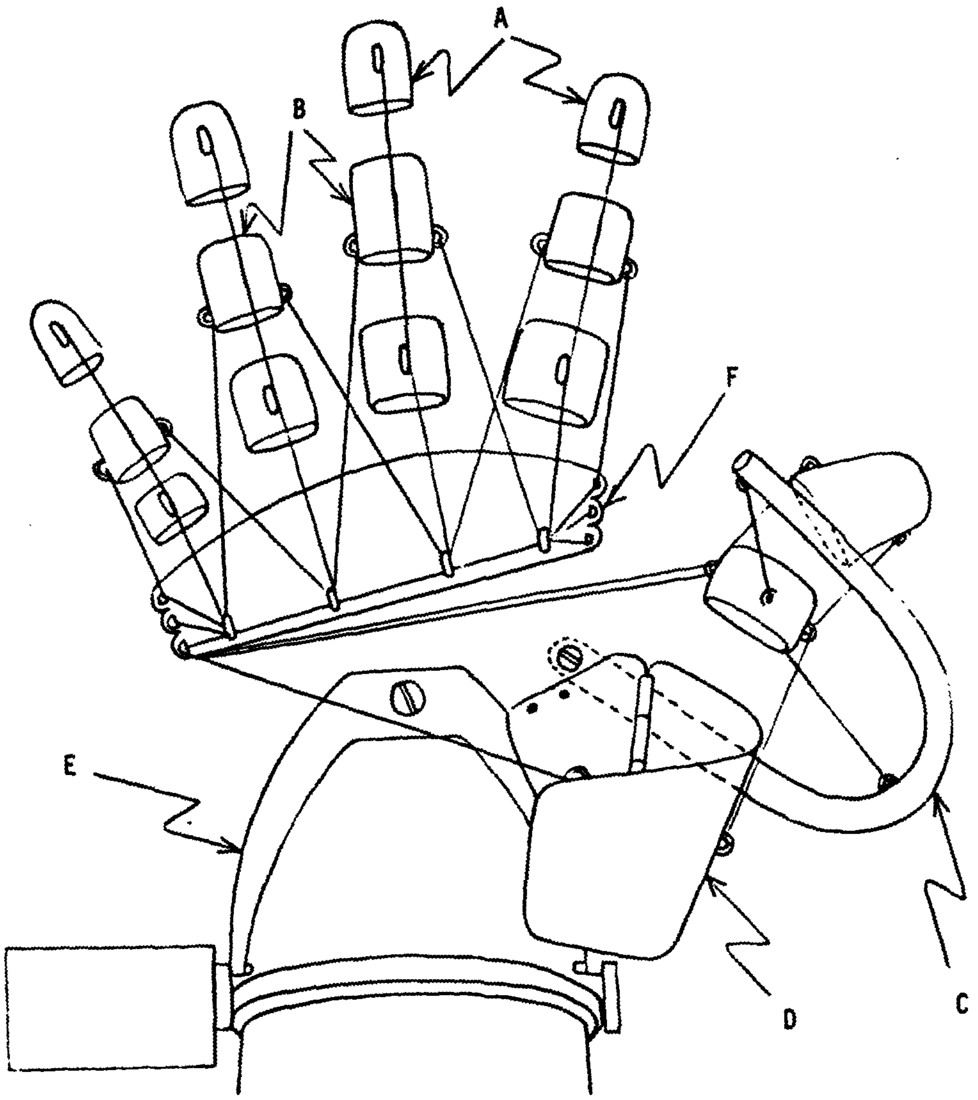


FIGURE 10 MASTER HAND CONTROLLER (BOTTOM VIEW)

A) FINGER THIMBLE DISTROL WITH ELECTROTACTILE DISPLAY
B) FINGER DISTROL RING
C) THUMB DISTROL OUTRIGGER TUBE
D) HINGED LOWER THUMB DISTROL
E) WRIST FLEXION-EXTENSION DISTROL
F) KNUCKLE BRACE

oppositional thumb. To provide a stable base with which to control thumb rotation and opposition to the palm, an outrigger base triangulates control cables for thumb opposition. Each phalanx is controlled for flexion and extension. In addition, Figures 9 and 10 illustrate the function of collateral cables which function in the control of abduction and adduction. The simultaneous activation of these degrees provides the capability of circumduction, required, for instance, in the grasp and manipulation of circular or cylindrical objects. Figure 9 illustrates the control of wrist abduction and adduction. The freedom of movement thereby produced approximates the 42 degrees of freedom ascribed to the human hand and wrist.

In addition to the control and positional information, tactile feedback at the fingertips is provided via an electrotactile display in the finger bands. Palmer contact and pressure, as previously discussed, is provided by the hydraulic system.

Interactions

The receptors and capabilities herein described represent a "minimal system" with no utilization of the structural interaction techniques of the neuromuscular system which serve to refine and define the information in an inherently noisy system (for review, see Békésy, 1968). While it is the presumption in the described advanced manipulator system that the operator be so tightly linked to the manipulator that he be able to perform the required integration himself, it is likely that despite the best engineering efforts, and because of the previously mentioned need for information filtering, the system will add some hysteresis to the incoming sensory data. The ability of an operator to adapt to such perturbations is well known, as are techniques to sharpen incoming data and to eliminate system generated noise. There may be a substantial time delay penalty to accommodate the required data processing. Despite the added complexity, it is our opinion that such techniques must be explored. Mechanical and electrical interactions which parallel neurophysiological sharpening may allow virtual information densities exceeding the mechanical display limitations.

As it is our opinion that the technology, if properly used, stands ready to provide a sense of operator presence, it serves this review to consider the interface between technology and the human operator neural structure. There are several physiological principles that might serve as models in information display.

The principle of structural interaction providing stability and accuracy in an inherently noisy system is elegantly demonstrated by the process of lateral inhibition. This phenomenon was first investigated by Ernst Mach in the context of vision during the late 1800's. Mach's findings, as explicated by Ratliff (1965), showed an edge enhancement at change of light intensity on the retina. The enhancement, a brighter or darker line at an illumination intensity edge, was effected by neural interaction in the retinal ganglion cells. This interaction is called lateral inhibition. In lateral inhibition, the retinal receptors in proximity to each other project inhibitory collateral axons to their neighbors. Those cells most affected by photic stimuli are most inhibitory of those cells adjacent to them. This inhibition provides a sharpening of the illumination difference among the receptors. The result is a perceptual demarcation of stimulus intensity change that has no physical corollary in the stimulus.

Similar networks of lateral inhibition were reported by Békésy (1960), and were later explored by him at length (Békésy, 1967). The sharpening of tactile stimuli by simulation of the biological transduction process has, as far as we have been able to determine through our research, been limited to one study by Clot, et al. (1975). We feel that investigation of preprocessing techniques at the peripheral sensors of the remote manipulator may lead to valuable information compression in display to the human operator.

In display to the human operator, parameters of stimulation are critical for information transmission. Temporal sequencing of stimulators to a neural structure, such as the mechanoreceptors of the skin, can induce an increase in stimulation densities beyond those physically presented. The concept of temporal coding in neural networks has been generally accepted in acoustics research. The acoustic frequency range of the human ear far exceeds a single neuronal absolute refractory period (Boring, 1965).

The temporal interactions of tactile presented stimuli are far less well established. Two phenomena are pertinent to our review. These, sensory saltation (Geldard, 1975) and the tactile phi phenomenon (Békésy, 1967), present the possibility of increasing display density without increasing physical stimulus area. In a two stimulator array, oscillation between one stimulator and another causes sensation of pressure at the two stimulator contacts, and at a third point between the two stimulators. Where that third stimulus is felt is a function of the phase difference between stimulators. This phantom stimulus has been dubbed the "phi phenomenon" by Békésy (1967). A related phenomenon has been investigated in depth by Geldard (1975). In this case, sensory saltation is described as a feeling of a phantom stimulation between two (or among more) stimulators that differ in frequency of stimulation. The sensation is described as a series of hops between the actual stimulators. The number and direction of the phantom stimulations is a function of the stimulus frequency difference. Neither of these phenomenon has been fully explicated, and both require a good deal of care in stimulus presentation, as well as some practice by the operator. Both, however, suggest methods of increasing display density without further operator encumbrance. Further, the saltation process provides a means of displaying directional information in tactile stimulation.

In addition to the physical interactions mentioned, the nervous system of the human operator displays an impressive capacity for integration of long term changes. For example, the process of sensory plasticity (Bach-Y-Rita, 1972) describes the capacity to "learn" a sensory experience in other than the "normal" mode of display. Bach-Y-Rita's work stems from efforts to produce a visual world for the blind via tactile stimulation. The use of alternative sensory modalities for display in order to unburden highly loaded channels, e.g., vision or audition, should be part of a total system investigation. Finally, there appears to be a strong learning function in sensory discrimination tasks. What has been taken as an upper limit for display density based on a sensory ability to discriminate may be increased by training (Solomonow, et al., 1979).

After prototype completion, there is required testing and evaluation of the laboratory model. This testing should be concentrated in the areas of:

- range of function offered by the multiarticulated master/slave controller
- psychological sense of presence generated in the operator
- performance improvement over standard remote system.

Evaluation of required "ruggedization" for field ready systems should also be instituted at this time.

EVALUATION AND CONSENSUS

Community Consensus

The survey of the state of the art of technology to promote a sense of operator presence in remote manipulation has led us to contact several leading research groups associated with the field. This effort was made so that we might obtain a balanced view of the direction of future research as well as a sense of the breadth of ideas of the current status of the field.

We present in this section information gathered from interviews with the research groups contacted. These interviews were conducted through telephone conversations, thus our record represents our interpretation of those conversations; we have, however, made a careful effort to maintain a high degree of accuracy.

Dr. William Spurgeon, Program Manager in charge of research directed toward automated production, National Science Foundation

Dr. Spurgeon maintains that, in relation to NSF's funding, and in view of current programs and conferences and the growth of private corporations, visual systems for robotic control are the primary area of emphasis in robotic automation. In particular, Dr. Spurgeon referenced the Hill (1980) survey on commerically available vision systems for robot control, a University of Rhode Island study on methods for robotic control with vision, and work by the Robot Institute of America on robotic production methods guided by visual systems. With respect to other sensors and production robots, Dr. Spurgeon mentioned only the work in the Charles Stark Draper Laboratories on compliant end effectors.

Dr. Charles Rosen, formerly of Stanford Research Institute Artificial Intelligence Laboratory, currently associated with Machine Intelligence, Incorporated, Mountain View, California

Dr. Rosen emphasized the flexibility and information density associated with visually directed systems. The problems of pattern recognition and transformation are being solved by "intelligent" algorithmic approaches. (The reader is referred to Winston, 1979, for a review of the artificial intelligence community's approach to visual processing.) While maintaining that redundant or supplemental information from tactile feedback modalities would be helpful, Dr. Rosen asserted the predominant importance of visual processing.

Dr. John Garin and Dr. Margaret Clarke, Oakridge National Laboratories, Oakridge, Tennessee

Doctors Garin and Clarke are involved with manipulator use in the context of nuclear materials handling at Fermi Labs. The manipulator provides electrical linkage with the master arm. Feedback is visual, and force reflection is by backdriving the master arm through the slave. At

Los Alamos, the industry standard Argonne Laboratories developed, mechanically linked, force reflecting feedback manipulator is used. Dr. Clarke is concentrating on visual feedback enhancement, interactive simulated graphics and visual image processing to aid the operator of the remote system.

Dr. Antal Bejczy, Jet Propulsion Laboratories, California Institute of Technology, Pasadena, California

Dr. Bejczy is directly involved with the sensing aspects of proprioceptive and tactile information. He works with systems that provide proprioceptive information both through electrically linked force reflection to the master arm, and through visual display of derived force/torque vectors. Tactile information is displayed visually; there has been no development of a tactile display homologous to the tactile sensor described in the body of this report.

Dr. Jim Koenamen and Dr. Jack Redman, Lord Corporation, Erie, Pennsylvania

Doctors Koenamen and Redman have been working on the development of an articulated hand and tactile sensors. Though the sensor information is company proprietary, we are informed that Redman's work involves decoupling the mechanical sensing substrate from the electrical transmission of the tactile information. The result of this separation will be a reduction in the nonlinearity, hysteresis and compressive set factors which plague conductive elastomers. The prototype model is sensitive both to normal and pattern loads, with a density of 0.3" (0.762 cm) on center. The expected density will be in the range of .15 inches (0.381 cm) on center, with both pattern and gray scale display. The system will detect shear on whole pattern of touch, or at each touch site. Again, the concentration is on the development of the sensor technology, not the display capability. In Redman's opinion, the system, which is expected to be made public sometime in January, 1981, represents the state of the art for touch sensing.

Dr. Frank Clippinger, Duke University, Durham, North Carolina

Dr. Clippinger was contacted concerning the possibility of direct neural interface between touch sensors on the slave arm and the human operator. Dr. Clippinger's work has been concentrated on functional electrical stimulation for paralyzed limbs via implanted electrodes, and, in prosthetics, the provision of the amputee with information regarding the state of the prosthetic system. He reports some success in the case of an amputee who, after some training, localized the electrically induced sensation as coming from the tip of his hook (this had to do with hook opening and hook closing). Patterns of tactile sensation have not been attempted. The medical difficulties associated with chronic implantation of stimulating electrodes appear to preclude their general use. Improvements in materials and stimulation methods may make such display feasible in the future.

Robot Institute of America, Dearborn, Michigan

The Robot Institute of America was contacted to find out about the industrial research commitment in robotics. This is part of our concern in relation to a future forecasting and development process with regard to industrial backing. The Robot Institute is a society established in conjunction with the American Society of Mechanical Engineers. The only major investment brought to light that has not been covered in the body of this report was a one million dollar grant from Westinghouse Corporation to Carnegie Mellon Institute for the study of human factors in robotics. Dr. John Lyman of the Biotechnology Laboratory, UCLA, had fortuitously been in contact with Dr. Lewis Hanes of Westinghouse in the late summer, 1980; in his opinion, the work funded concerned man/machine industrial interface, for example, work schedule, layout, batch production, etc. Ms. L. Mei of the Robot Institute knew of no other research that has not been covered previously in this report. She did, however, mention the University of Florida studies (also mentioned by Doctors Garin and Clarke of Oakridge National Laboratories), where work being done under the auspices of the U. S. Department of Energy is not made available to extra governmental agencies. We recommend that NOSC procure these records; the contact is Dr. William Boyian, Department of Engineering Sciences, Control Engineering, University of Florida, Gainesville, Florida, 32601, Telephone: (904) 376-3199.

Opinion

There is sufficient technology at the present time to make a laboratory prototype of an operator "present" arm possible. Strong driving forces in industry for automated production methods have arisen. This trend is evidenced by recent publicity in the news media, for example. Time, Newsweek, Circuits Manufacturing, Robotics Age, Science Digest, and OMNI magazines all have featured stories recently on the need and potential for industrial and other types of robotics. Momentum and capital sufficient to produce high quality and reliable components for manipulation and tactile sensing are evidently to be a part of the next decade. Making the components able to endure hostile environments is required as a part of the overall effort. The evidence we have assembled suggests the major area lacking in the successful achievement of a remotely projected operator presence is the tightly linked display to the operator of the remotely sensed environment. Research is needed in the areas of tactile and proprioceptive display configuration, density, coding, balance, and fidelity. The process of displaying a complex tactile model of a task environment to a human operator of a remote manipulator system has not been previously attempted. We see no reason why such a display should not be possible, and we feel that the technology available for information display awaits only improvement in techniques of human operator interface.

Forecasting Options

Several methodologies for futures forecasting have been developed and are in current use (Armstrong, 1978; Fowles, 1978). These techniques are applied because their systematic use provides more valid results than reliance on random guesses or on an individual's opinion. Some of these techniques could be appropriately applied to assessing current technological capability to realize an advanced manipulator system, but time and monetary constraints have precluded their use in this study.

One of the techniques is the Delphi method, which can be constructed as an iterative series of questionnaires. By polling experts, but maintaining anonymity of specific opinions, consensus is reached without undue influence of normal group dynamics. Unorthodox opinions are more likely to be considered on their own merits, rather than to be accepted or rejected on the basis of their sources. Effects of forceful personalities and pressure to conform are reduced. The iterative nature of the survey contributes to the achievement of consensus among the polled experts.

In the context of development of remote presence systems, a Delphi survey could establish the consensus in the field as to when the conditions necessary for building an advanced manipulator system will be realized, based on current trends and resources. The survey could also identify the perceived areas where funding is most needed.

Another methodology which has been applied to technological assessment for the past decade (Enzer, 1972) is known as cross-impact analysis. If the conditions for an advanced manipulator system can be defined as events, e.g., development of articulated end effector, then a Delphi survey could be used to supply the data necessary for a cross-impact analysis of the effects of various policy decisions.

Cross-impact analysis models the future as a set of events; any particular "future" within the field of interest can be represented by designating a specific subject of events that "has occurred." For example, if A, B and C are possible events, one future would be "C has occurred, A and B have not occurred." The relationships between events are modelled using Bayesian probability theory, and some simplifying assumptions, to make the analysis computationally tractable. A policy influencing the future is described by modifying the initial probability of occurrence of an event or set of events.

The cross-impact methodology includes the following steps: Choose a set of events, deemed relevant to the situation under consideration. Assign each event an a priori probability of occurring within the given time period; also assign each event an a posteriori probability of occurrence given each other event has occurred. Check these probabilities for consistency. Then conduct several simulation runs; tabulate the frequency of occurrence of the various events. To test the effects of various policies, alter the initial probabilities of some events and conduct many runs.

The algorithm is defined more specifically in this paraphrase from Stover and Gordon (1978):

1. Define the events to be included in the analysis (perhaps through a Delphi study).
2. Estimate P(event i), the initial probability of each event i occurring.
3. Estimate P(event i/event j), the conditional probability for each event pair. This is the probability that event i occurs, given that event j is known to have occurred.
4. Perform a calibration run on the cross-impact matrix constructed from the above probabilities. Compute the non-occurrence matrix from the known probabilities and the relationship:

   P(event i/event j did not occur) =

   $$\frac{P(\text{event } i) - P(\text{event } j) \times P(\text{event } i/\text{event } j)}{P(\text{event } j \text{ did not occur})}$$

   a. Compute odds occurrence matrix and odds non-occurrence matrix from previously calculated probability matrices.
   b. Select one event at random.
   c. Select a random number R between 0 and 1 to determine the occurrence of the chosen event:

      If P(selected event i) $<$ R then event i occurred
      If P(selected event i) $\geq$ R then event i did not occur.

d. Adjust odds of other events as their chances of occurring are influenced by event i:

New odds of event j = (old odds of event j) X
(appropriate odds occurrence or
non occurrence ratio)

e. Repeat steps (b), (c), (d) until all events have been tested for occurrence.

f. Repeat steps (b) through (e) many times to achieve a statistically significant series of simulations. Compute the relative frequencies of the events from the compiled results of the runs. These relative frequencies define the adjusted overall probability of occurrence for each event.

5. Formulate policies and actions to be tested on the cross-impact matrix. This can be done by adjusting the probabilities of events over which policy makers are likely to have control.

6. Repeat (4) using the policy-adjusted cross-impact matrix. Do this with the various possible policies that have been identified.

7. Evaluate results of simulation runs.

Application of Methodology to Advanced Manipulator System Forecasting

If cross-impact analysis were applied to forecast the capability to construct an AMS, and the effects of various policies on that capability, we could model the requirements for an AMS as a set of events. The specific research contract for the present study limits our time horizon to ten years; creation of an AMS could then be represented as the occurrence of a set of events by 1990. Some of these events would directly impact the ability to construct a "presence" system, e.g., the advent of conductive elastomers with low hysteresis, high linearity, and sufficient operating life to be practical as tactile sensors. Many, if not most, of the events would be precursors to the events that represent an actual technological capacity for an advanced manipulator system, e.g., achievement of funding level X for development of conducting elastomers may be a prerequisite event to the advent of those elastomers. Identification of relevant events could be accomplished by combining the knowledge derived from our state-of-the-art survey and conceptual design with a Delphi study involving experts in the related fields. The probabilities of these events, and their impact on each other, could be estimated from the same sources.

The choice of resource-allocation policies to be evaluated would depend on the available resources. Any monetary or non-monetary resource strategy which had a reasonable chance of significantly affecting event probabilities could be assessed. Each policy would be expressed by altering the initial probabilities of the corresponding events. The compiled cross-impact runs with these new probability values would result in sets of updated probabilities for the events required for an AMS.

Once all simulation runs had been completed, the various policies could be rank ordered in terms of relative success for contributing to the realization of an AMS within ten years. This ordering might be achieved by use of a utility weighting function that weights more important events more heavily than other events. Based on the ranking of the policies, specific policies could be selected to most increase the liklihood of successful development of a remote presence system within the allotted time period.

SUMMARY

In this report we have reviewed the state of the art of controls, effectors, sensors, and displays for human operator control of a remote manipulation system. The project directive was to structure the review with the end in view to induce in the operator of such a system a sense of immediacy or presence at the remote task site.

It is our opinion at the conclusion of this review that the technology required to produce such operator presence is currently available. Our opinion is tempered by the consideration that the interface specifications among the human operator, slave, and master systems can only be approximated. There is no full theory or modelling effort from which to deduce the exact performance to be expected of such a complete and tightly linked system.

It is our suggestion that work proceed with the development of a prototype system using currently available technology. Performance tests with the prototype will lead by an iterative process to specifications for system improvement.

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APPENDICES

APPENDIX A

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APPENDIX B

ROBOT INSTITUTE OF AMERICA INFORMATION

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ACHIEVEMENT OF A SENSE OF OPERATOR PRESENCE IN REMOTE MANIPULAT--ETC(U)
OCT 80 K CORKER, A MISHKIN, J LYMAN N66001-80-C-0265
UNCLASSIFIED UCLA-ENG-8071 NL

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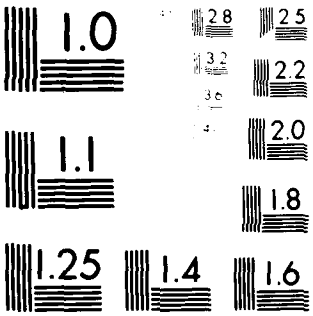

MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

PRELIMINARY RESULTS OF WORLDWIDE SURVEY

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PRELIMINARY RESULTS OF WORLDWIDE SURVEY

The decision to conduct a survey on worldwide robots was reached at the March 12, 1979 meeting of the National Coordinators in Washington, D.C. (USA).

The survey questions were designed to provide the National Coordinators with information about the world's robot population, definitions, formal organizations, government support of research and the formation of an international Federation of Robotic Organization.

The following countries are included in the results of this survey: Belgium, England, Finland, Japan, Norway, Poland, Sweden, United States and West Germany. It is realized that in many instances terminology and definitions may differ.

TYPES OF ROBOTS

Chart A divides the robot population according to countries. Please keep in mind that the figures given are estimates.

Chart "A"

	Type A	B	C	D	E	Total
Japan	3,000		11,000		33,000	47,000
West Germany	300	150	200	200	5,000	5,850
United States	1,810	345	1,100	*	*	3,255
England	60	85	20	20	*	185
Poland	70	40	200	50	360	720
Belgium	7	3	*	3	7	20
Sweden	450	120	*	*	*	600
Norway	20	20	100	30	30	200
Finland	20	10	70	10	20	130

*Figure unavailable

Type A:	Programmable, Servo-Controlled, Point-to-Point
Type B:	Programmable, Servo-Controlled, Continuous Path
Type C:	Programmable, Non-servo Robots for General Purpose
Type D:	Programmable, Non-servo Robots for Die Casting and Molding Machines
Type E:	Mechanical Transfer Devices (Pick-and-Place)

ROBOT DEFINITIONS

Three organizations have adopted a formal definition of robot.

> "Industrial Robots are programmable machines having several (more than 2) degrees of freedom, with grippers for workpiece handling or tools for manufacturing." (West Germany)
>
> "A Robot is a reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks." (United States)
>
> "A Robot is a handling manipulator with an electronic, direct programmable control unit, all possible to move from one workplace to the other for flexible use on different tasks." (Norway)

The following definitions are under consideration or are general definitions relating to the technology in that particular country.

> "A machine formed by a mechanism including several degrees of freedom, often having the appearance of one or several arms ending in a wrist capable of holding a tool or workpiece or an inspection device, and sometimes it can use sensing and adaptation appliances taking into account environment and circumstances. These multi-purpose machines are generally designed to carry out a repetitive function and can be adapted to other functions." (France)
>
> "The industrial robot is a device for moving, (with a considerable speed and limited precision), objects or tools in at least three degrees of freedom; both the extent of the movements and their order of sequence are programmable or adjustable within the working range." (Finland)
>
> "A machine with one or more arms each with several degrees of freedom plus a wrist with one or more degrees of freedom, which can be reprogrammed to alter both its sequence of movements and the dimensions of those movements. Also it is capable of performing a variety of functions." (United Kingdom)
>
> "A robot is treated as a system which is able to perform manipulation and locomotion functions or a determined level of machine intelligence. A robot is a certain cybernetic machine whose versatile and adaptive properties enable it to simulate some of the functions of the human being. Industrial robot: automatic handling unit which is freely programmable in several degrees of freedom; sequence of the motion of the different axes and the distances travelled in the different axes has to be variable." (Poland)
>
> "A robot is a universal machine with grippers or tools; 4-6 degrees of freedom, easily and independently programmable in each degree; and has a repeatable precision of position of 0.01-0.1 mm (small units), 0.1-1 mm (large units)." (Belgium)

Chart B indicates the classifications and definitions of robots for Japan.

Chart "B"

1. Manual manipulator	Manipulator which is directly operated by a man.
2. Sequence robot	Manipulator the working step of which operates sequentially in compliance with the present procedure, conditions, and positions.
a. Fixed sequence robot	Sequence robot as defined above, the preset information for which cannot be easily changed.
b. Variable sequence robot	Sequence robot as defined above, the preset information for which can be easily changed.
3. Playback robot	At first, man teaches the manipulator the working procedure through directly operating it, so that the robot itself memorized the procedure; then it can continuously repeat its operations.
4. NC robot	Manipulator which can execute the commanded operation in compliance with the numerically loaded working information about position, sequence, or condition.
5. Intelligent robot	Robot which can decide its behavior by itself through its sensing and recognizing capacity.

(NOTE)

Manipulator	A "manipulator" performs a function similar to that of human upper limbs. It has more than two of the motion capabilities, such as revolving, out-in, up-down, or right-left traveling, swinging, and bending, so that it can spatially transport an object by holding it, adhering to it, and otherwise.

When questioned about the need for an international definition for the word robot, eight countries agreed that there is a need, while one country disagreed. Seven countries felt an agreement could be reached among the various organizations, while one country disagreed and one was uncertain.

GENERAL COMMENTS

All 9 countries reported that either their government or an agency provided research funds for robotic development. However, only five of those countries had a formal robotics organization, institute or association operating or being formed in their country. When asked about the formation of an International Federation of Robotic Organizations, five supported the idea, two did not support it, and two were uncertain.

Comments against the formation of an international Federation of Robotic Organizations included the suggestion that it should first be studied if an affiliation to an existing international federation like the International Federation of Automatic Control would be more warranted.

Reasons supporting the formation of an international Federation included the opportunity to organize subcommittees for the standardization of terminologies, hardware elements, application technology and so forth. Also a federation could execute international cooperative research projects. Managing the ISIR's systematically and smoothly could also be a function. Problem solving and assessment of robot applications in production systems could be highlighted in activities. Only close cooperation between countries for the exchange of information will enable further progress in the development of robotics and manufacturing for the future generations of industrial robots.

Since the preliminary results of this survey consists of only 9 countries, it shall be followed up with a more inclusive report as additional surveys are submitted. We would like to encourage those who have not submitted their surveys, to please do so, in order to gain an accurate perspective on worldwide robotic technology. The National Coordinators will receive a copy of the final survey results as soon as they are available.

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*indicates a formal robotics organization in that country

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