20 June 1980, Volume 208, Number 4450 SCIENCE

Sensors, Controls, and Man-Machine Interface for Advanced Teleoperation

Antal K. Bejczy

The term "teleoperation" is used to describe mechanical activities performed by mechanical devices at a remote site under remote control. The remotely performed mechanical actions are usually associated with the normal work function of the human arm and hand. Thus teleoperation extends the manipulative capabilities of the human arm and hand to remote, physically difficult, or dangerous environments.

Summary. Some advances have been made in teleoperator technology through the introduction of various sensors, computers, automation, and new man-machine interface devices and techniques for remote manipulator control. The development of dexterous articulated mechanisms, smart sensors, flexible computer controls, intelligent man-machine interfaces, and innovative system designs for advanced teleoperation is, however, far from complete, and poses many interdisciplinary challenges. This article summarizes the state of the art, gives a brief outline of the basic problems, and presents the results of teleoperator research and development at the Jet Propulsion Laboratory.

The first teleoperator systems were developed about 35 years ago to allow an operator to handle radioactive materials from a workroom separated from the radioactive environment by a concrete wall. The operator observed the work scene through viewing ports in the wall. The development of teleoperator devices for handling radioactive materials culminated in the introduction of bilateral (force-reflecting) master-slave manipulator systems (*1-3*). In these very successful systems, the slave arm at the remote site is mechanically or electrically coupled to the geometrically identical or similar master arm and thus follows the motion of the master arm. But the coupling between the master and slave arms is two-way: inertia or work forces exerted on the slave arm can back-drive the master arm. Hence the operator holding the master arm can feel the forces acting on the slave arm. This is an essential requirement for dexterous control of remote manipulators, since general-purpose manipulation consists of a series of well-controlled contacts or "collisions" between the handling device and the objects.

Master-slave teleoperator technology has been expanding to accommodate new telemanipulation requirements in space, under the sea, in nuclear facilities, and in other frontiers of science. This is reflected in a recent NASA study (*4*) that described a teleoperator as

> a robotic device having video and/or other sensors, manipulator arms, and some mobility capability, which is remotely controlled over a telecommunication channel by a human operator. This human operator can be a direct in-the-loop controller who observes a video display of the teleoperator and, with joystick or analog device, continuously controls the position of the teleoperator vehicle, its arm, or its sensor orientation. Alternatively, the teleoperator can employ a computer, endowed with a modicum of "artificial intelligence," capable of executing simple control functions automatically through local force or proximity sensing; in this case, the remote human operator shares and trades control with the computer.

A number of studies have identified advanced teleoperation requirements for projected space missions (*5*). Teleoperators would be invaluable in satellite retrieval, servicing, or maintenance; deploying or assembling space platforms, space stations, large antennas, and solar power stations; exploration of lunar and planetary terrains and materials; scientific experiments and analysis of space materials in sealed space laboratories; and rescue operations in space. [For advanced applications of teleoperation under the sea, see (*6*); for applications to cope with new demands for remote maintenance and repair operations in nuclear facilities, see (*7*).]

This article focuses on an important aspect of advanced teleoperator technology: remote manipulation, including the mechanism, sensors, control, human interface, and operational context. The enumeration of these "subsystems" indicates that the development of advanced teleoperator technology is an interdisciplinary challenge. But, like the creation of a new tool, it will not be the simple sum of other technologies. It represents a field of applied science and engineering in its own right, and requires its own experimental base.

The basic problems and issues in advanced telemanipulation can be summarized under three major categories: mechanisms, sensors and control, and man-machine interface.

Mechanisms

In general, manipulators are intricate mechanical devices and pose many mechanical design challenges. Although thousands of manipulators are being used in nuclear, automotive, and other industries around the world, many unsolved practical and theoretical problems remain. These problems concern linkage and joint geometry, kinematic re-

Antal K. Bejczy is a member of the technical staff at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena 91103.

0036-8075/80/0620-1327$02.00/0

dundancy and dexterity, structural stiffness and dynamics, actuators for power and precision, motion transmission within the manipulator, mathematics for geometry and dynamics of mechanical arms, properties of end effectors, and mechanical evaluation criteria. The research and development community has paid increasing attention to these and other mechanical issues during the past few years (*8–10*).

The need for more advanced teleoperators broadens the mechanical design challenges considerably. For example, projected applications in space will require four to five different sizes of manipulators—from giant crane-like mechanisms capable of extending 50 meters or more to minimanipulators capable of handling millimeter-sized objects. At issue are such matters as whether these manipulators (in particular, the large ones) should be inherently flexible structures, and how mechanically dexterous end effectors should be in order to deal smoothly and efficiently with objects of greatly differing shape, inertia, and stiffness.

Today's manipulators are first-generation machines. They are mere multiaxis transfer devices and are designed as purely mechanical tools. The few external sensors mounted to some mechanical arms and hands are mechanically treated as attachments rather than as elements of an integral system. To advance the state of the art toward greater dexterity, the dual tool/sensor role of a mechanical arm/hand system should be firmly recognized. Even the mechanical features of the arm/hand system play a functional role in sensing and control during manipulation.

Sensors and Control

Manipulation means geometric and dynamic interaction with the environment. To control this interaction successfully requires the use of both visual and nonvisual sensor information. The visual information for manipulator control is essentially geometric. It relates to the control of gross transfer motion of the mechanical arm in the environment

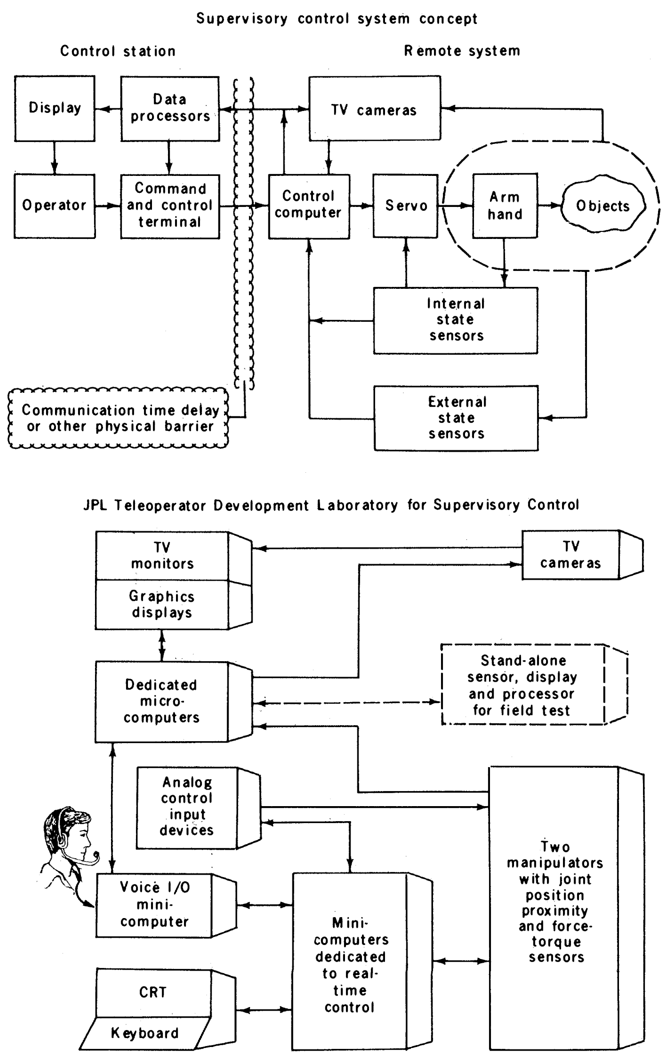

Fig. 1. Elements and organization of the JPL teleoperator laboratory.

and to the orientation of the mechanical hand relative to environmental or object coordinates. Visual information is obtained directly or through stereo or mono TV, and can be supplemented with information from ranging devices.

The nonvisual sensor information is used in controlling the phsyical contact or near-contact of the mechanical arm/hand with objects in the environment. It is obtained from proximity, force-torque, and touch-slip sensors integrated with the mechanical hand. These sensors provide the information needed to perform terminal orientation and dynamic compliance control with fine manipulator motions. The information from these sensors is directly referenced to the coordinates of the mechanical hand. The integration of visual and nonvisual sensor information for control is an important goal.

Terminal orientation and dynamic compliance control are essential and intricate elements of manipulation. Soft and adaptive grasp of objects, gentle load transfer in emplacing objects, assembling or disassembling parts with narrow tolerances, and performing geometrically and dynamically constrained motions (like opening or closing a latch or fitting two parts together) are typical examples of manipulator control problems that challenge both sensor and control engineering. To fulfill the requirement for manipulating extended and flexible structures in the weightless environment of space, manipulator sensor and control systems with adequate geometric precision and dynamic compliance will have to be developed.

Manipulator control is very difficult to achieve. It requires the coordinated control of several (typically six) manipulator joints. The relation between work-space coordinates (which define the task) and joint-position variables (which define the control) is given by complex trigonometric transformations. Further, the dynamic properties of manipulators vary with the joint-position variables. The result is that the motion dynamics of a mechanical arm with n degrees of freedom is mathematically expressed by n coupled, highly nonlinear, second-order differential equations—and each equation can contain many variable terms. To deal with complex multivariable trigonometric and dynamic calculations in real-time computer control programs requiring update rates of 50 hertz or more is nontrivial, and invites specific considerations for both software and hardware architecture. It also invites new approaches to the mathematical description of manipulation tasks, including the kinematics and dynamics of manipulators.

Several modes of control have been developed for mechanical arms. In the manual mode, all control originates from some analog manual input from the human operator. In this mode the most successful technique is the force-reflecting master-slave control widely used in the nuclear industry. In another widely used control mode, the program-controlled industrial "robot" mode, the manipulator endlessly repeats a fixed sequence of motions without operator intervention. The success of this control mode is anchored to the fact that some manipulative tasks can be and are precisely prearranged in space, time, and dynamic conditions in a given industrial environment. In this control mode the manipulator cannot automatically adjust its motion to changes or variances in the task conditions, since it does not sense them. It works slavishly. Changes or variances in external task conditions cause the robot arms to stop or jam the work.

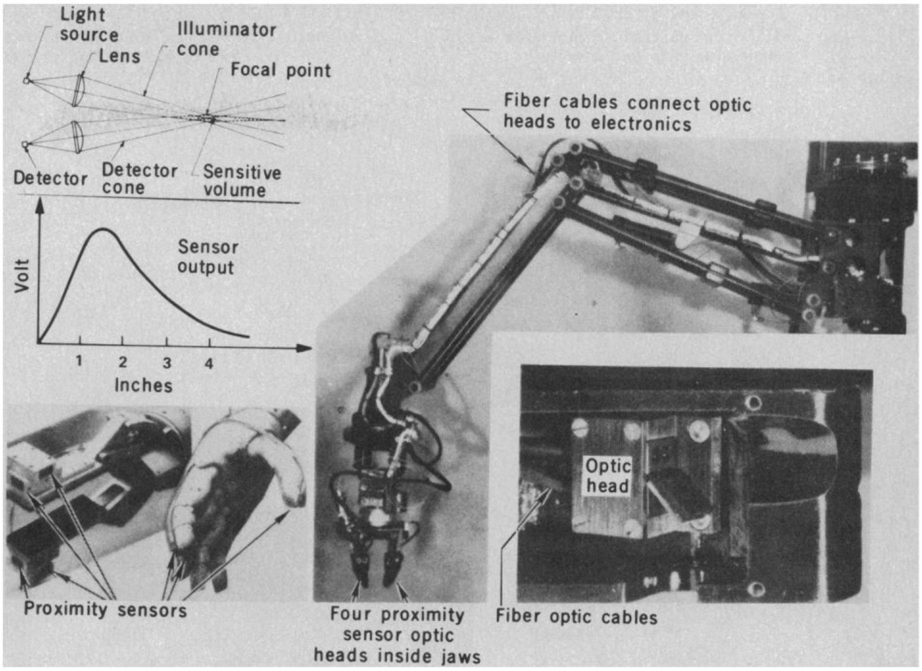

Fig. 2. Proximity sensor concepts and implementation examples.

Current development efforts by several major laboratories are focused on sensor-referenced and computer-controlled (SRCC) manipulators (*10–16*). Some simple SRCC manipulators already exist. This advanced control mode has great potential to extend the use of mechanical arms far beyond the domain of strictly repeatable tasks. However, the present state of SRCC manipulator technology must be regarded as primitive. First of all, much better exteroceptive sensors for manipulator control are needed (*16, 17*). The improved sensors should also have the fast data preprocessing "intelligence" required for real-time control. It should be mentioned that hand-based sensors generate time sequences of multidimensional data. In general, it is a nontrivial task to process and transform multidimensional (and often noisy) data to appropriate control reference inputs in real time. Hence, to have a sensor sufficiently "smart" for manipulator control, the sensing elements should be coordinated with sensor data processing for real-time operation.

Automation in the SRCC manipulator mode requires the development of control algorithms containing many numeric and nonnumeric (logic) expressions and calculations. The design and real-time implementation of such control algorithms raises a number of problems. A central problem is how to deal with the richness of task scenarios facing a general-purpose manipulator. An important aspect of this is the selection of decision parameters to be made available to the operator who will use the control algorithms. Another problem is the lack of techniques for deriving and evaluating control laws by using feedback from external sensors so that stability of motion conditions is satisfied. Control laws of this kind are still developed on an ad hoc basis, and their verification or improvement requires extensive simulation or experimental tests.

Man-Machine Interface

Advanced teleoperation invites new developments in interfaces between human operator and sensor- and computer-augmented control of remote manipulators (*6, 18–21*). The interface problem can be viewed in terms of a "control station" where control decisions are based on information feedback, control commands are issued to achieve a task goal that takes available resources into account, and performance is monitored.

The normal manual dexterity of humans is more a "body" skill than an intellectual one. The man-machine interface philosophy embodied in the force-reflecting master-slave manipulator control technology has been founded mainly on this fact. Advanced teleoperation employing SRCC manipulators shifts the operator-manipulator interface from the body (analog) level to a more intellectual (symbolic) level. Developers of new man-machine interface technology for advanced teleoperation will have to render the symbolic interface between operator and manipulator as efficient as the conventional analog interface.

Researchers in this area face four basic challenges: (i) construction of sensor information displays in integrated, easily perceivable, and task-related forms; (ii) construction of efficient and simple control/command languages tailored to the mechanical, sensing, and electronic properties of the manipulator and to anticipated task scenarios; (iii) construction of hybrid (analog/symbolic) interfaces to intensify the operator's command capabilities; and (iv) extending man-machine communication to audiovocal channels in order to deal efficiently with the demands of an increasingly complex control and information environment.

Advanced Teleoperator Development at Jet Propulsion Laboratory (JPL)

Motivated by space application requirements, JPL has been engaged in an advanced teleoperator development program for the past 7 years. The specific objective of this program is to advance the state of the art by developing and evaluating flexible, sensor- and computer-aided manipulator controls, "smart" mechanical hands with "smart" sensors, and efficient man-machine interfaces. A few mechanisms-related projects are also ongoing at JPL (*22*).

The computer-aided manipulator control development is pursued within the framework of a "supervisory control system" (Fig. 1) (*23*); that is, the operator can share or trade control with the computer and may also use manual (ana-

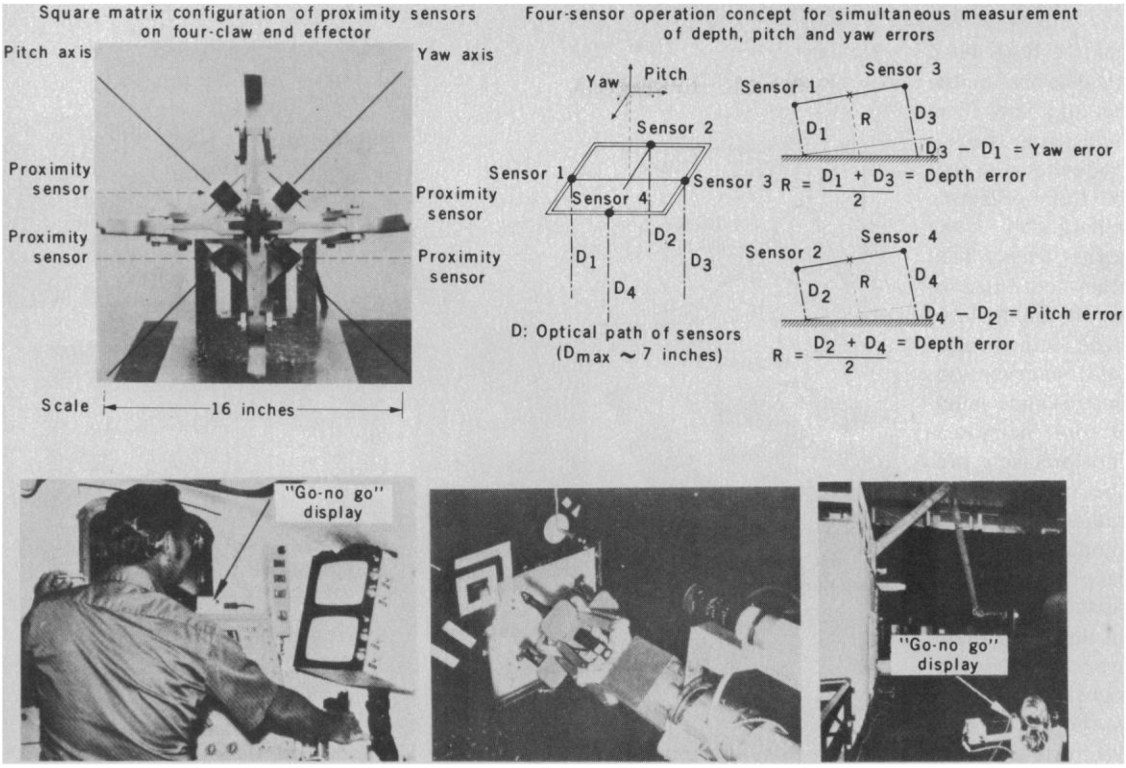

Fig. 3. Proximity sensors for space shuttle remote manipulator system application.

log) control input devices. Shared control means that the computer is in series with the operator and transforms or modulates the operator's functional commands. Traded control means that the computer executes control functions automatically based on a programmed "control intelligence" that can be referenced to terminal/compliance sensor information.

Figure 1 provides a brief overview of the components and organization of the JPL teleoperator laboratory. As can be seen, the development and use of various sensors (proximity, force-torque, touch-slip) are central to the program. A network of mini- and microcomputers handles sensor data processing and control computations in real time (*24, 25*). Table 1 gives a complete list of the equipment components of the laboratory.

Proximity Sensors and Control

Figure 2 illustrates the basic concept of electro-optical proximity sensing together with several examples of implementation and application (*12, 26*). The proximity sensors perform their function by beaming infrared light of constant intensity onto the target and measuring the amount reflected; the intensity of the reflected light is a function of the sensors' distance to the target. In actual implementation, the optical head of the sensor produces a narrow, cigar-shaped sensitive volume permanently focused a few centimeters in front of the sensor. The sensor is mounted to an appropriate place on a mechanical hand and generates a voltage signal when the sensitive volume "touches" a solid surface as the mechanical hand approaches the surface. The voltage generated is a nonlinear function of the distance between sensor head and object.

Figure 2 also shows a new proximity sensor design. In this design, the light source and light detector have been removed from the optic heads (located inside the claws) and integrated into the electronics instrumentation near the computer interface. An optic head consists of two 2-mm lenses with an 8-mm gap between the optical axes. Fiber optic cables of low attenuation connect the light source and light detector to the optic head. The round-trip distance from light source to optic head and back to detector is about 12 m in the implementation shown in Fig. 2, but can be much longer if necessary. Application of fiber optics has considerably improved signal quality and simplified instrumentation.

In the new design, the optic heads of the sensors are placed inside the claws so that the optical paths to the outside run through holes in the claws. The optic heads inside the claws are mounted so that the length of the optical path inside the claws equals the distance measured from the optic head to the point where the sensor voltage output is maximal; that is, where the top of the bell-shaped signal curve is located. In this arrangement, only the outer leg of the signal curve can be utilized for distance sensing. This arrangement, therefore, eliminates the possibility of double-valued distance reading. The optical paths that go "down" from the claws are projected through small mirrors inside the claws. This construction results in a more compact and symmetric sensor-claw integration.

Proximity sensors have also been developed at JPL for possible use on a 16-m mechanical arm aboard NASA's Space Shuttle during payload handling or satellite retrieval operations. The purpose of the sensor system is to aid remote control of the mechanical arm by indicating to the operator whether the end effector (a grapple, claw, articulated hand, or other grasping device) is near to and aligned with the target to be grasped or captured.

The system uses four proximity sensors (see Fig. 3) in a square-symmetric arrangement on a four-claw mechanical hand integrated with a 16-m articulated mechanical arm developed by the Johnson Space Center Manipulator Development Facility. This arm simulates the function of the Shuttle Orbiter Remote Manipulator System. The sensor system provides simultaneous measurements of range, pitch, and yaw errors of the mechanical hand relative to the target, and supplies the guidance and control information necessary for successful grasp near the grasp envelope, where visual perception of depth, pitch, and yaw errors is poor.

The electronics and data processing logic handled by a microcomputer are set to indicate, by a buzzer and a green light, when, during the approach to the target, the combination of depth, pitch, and yaw errors guarantees success of target capture. At that time, the four-claw and effector are closed by the operator.

Ground tests were conducted with the sensor and simple "success" display system at the Johnson Space Center under realistic payload-handling conditions. The system was effective both for grasping stationary loads and capturing moving targets (*27*). Further successful tests were conducted with a graphic and numeric display system developed recently. This display shows range, pitch, and yaw error values and indicates whether the simultaneous combination of these three errors will allow a successful grasp. The new displays enable the operator to finely control the grasp to prevent preloading the target when it is grasped.

Computer control programs referenced to proximity sensors have recently been developed for automatic tracking and capturing of slowly moving heavy targets (*28*). The computer programs provide an interactive manual and automatic control capability so that the operator can decide on-line when and at what level the automatic control should be activated or deactivated. Soon, force-torque sensor data will be used to decelerate and stop the moving object gradually and gently.

Force-Torque Sensing and Control

A six-dimensional force-torque sensor (*29*) has been integrated with the JPL/CURV mechanical arm, which has 6 degrees of freedom. This sensor resolves forces and torques exerted by the mechanical hand on objects along three orthogonal axes referenced to the mechanical hand. The dynamic range of the sensor is 0.5 to 300 newtons.

The sensor has the configuration of a Maltese cross and is machined from one piece of aluminum to reduce hysteresis. The sensitive elements consist of semiconductor strain gauges mounted on the four deflection bars of the cross. There is one gauge on each side of each of the four deflection bars, giving a total of 16 gauges. The gauges on opposite sides of a deflection bar are wired in voltage-divider pairs, providing a single reading that reflects differences in strain levels on the opposite sides of the bar. Thus, the sensor provides eight output readings, which can be resolved through a six by eight calibration/transformation matrix into three orthogonal force components and three orthogonal torque components referenced to a sensor or mechanical-hand coordinate frame. Under ideal conditions, only 16 elements of the six by eight transformation matrix are of significance.

Force-torque sensor information is being used in both manual and computer control modes, and is displayed to the operator in real time on a graphics terminal in both control modes. The display shows all orthogonal force and torque components in numerical and graphic form. The latter consists of a set of six horizontal bars, one bar for each force and torque component; the length of

Table 1. Equipment components of the JPL advanced teleoperator development laboratory. All are operational unless otherwise indicated.

Workroom	Remote control station
Humanoid slave arm	Exoskeleton master arm
CURV linkage arm	Universal control panel
Parallel jaw hands	Convertible hand controller
Swinging hand	TV, pan tilt, zoom control
Humanoid hand	TV displays, stereo and mono
Stereo TV cameras	Audio and visual displays for four proximity sensors
Mono TV cameras	Visual display for directional slippage sensors*
Proximity sensors	Visual display for multipoint proportional touch sensor
Touch sensors*	Force-torque sensor visual display
Force-torque sensor	Teletype and CRT for computer command
Slippage sensors*	Voice command system
Minicomputer, Interdata M70	Voice feedback system
Control programs	Color graphic terminal
Minicomputer Nova 2	Force-reflecting position hand controller†
Microprocessor, Cromemco Z-2	
Disk memory	
Fast line printer	
Minicomputer, PDP 11/40†	
Minicomputer, Interdata 8/16†	

*Bench model; partly operational. †Under development.

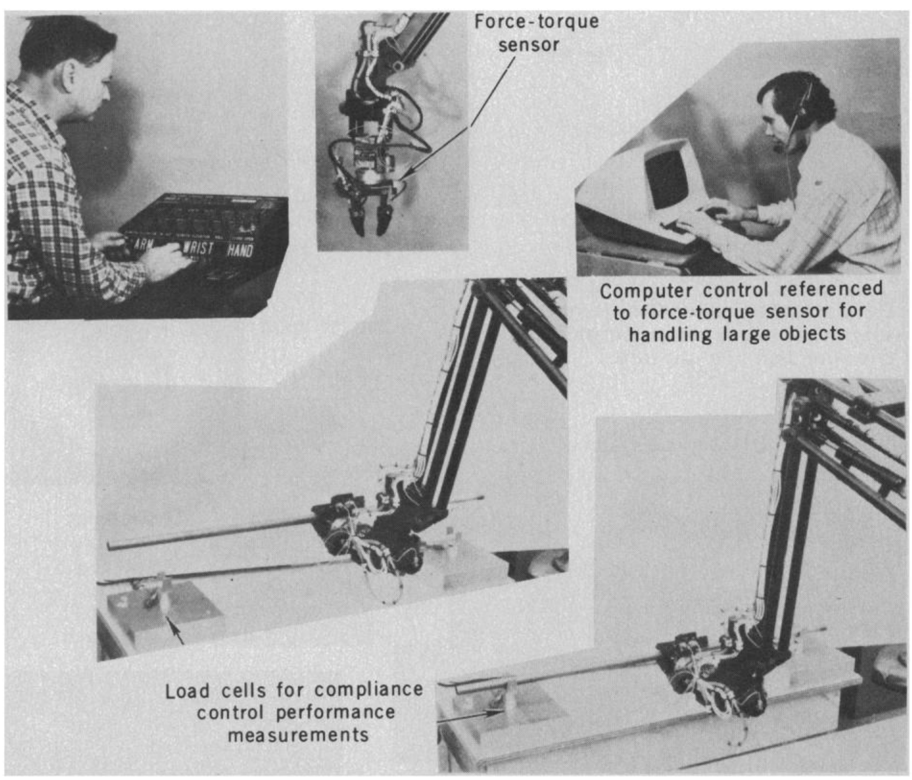

Fig. 4. Handling of large object, with guidance from a force-torque sensor in the computer control mode.

each bar is proportional to the numerical value of the corresponding force-torque component. The bars originate from a vertical line down the center of the TV screen. To the right of this center line, the force-torque field is positive; to the left, it is negative.

Computer control programs have been developed at JPL for experiments in which large objects are handled in order to study collision or impact dynamics. The task scenario involves long, linear objects (like beams) emplaced by the manipulator on two widely separated jigs. Figure 4 shows that, in the case of handling large objects, the observation or specification of a single point in the work space is insufficient for manipulator control. Note also that the touchdown of the pipe on the jigs is not easily seen. But the force-torque sensor provides instantaneous and precise information on touchdown and also tells where contact occurred first. Misalignment of the pipe is automatically corrected by a computer program referenced to force-torque sensor data, ensuring a parallel and soft touchdown or load transfer.

Force-torque sensor information is of vital importance in controlling all dynamically constrained operations (such as fitting or assembling parts).

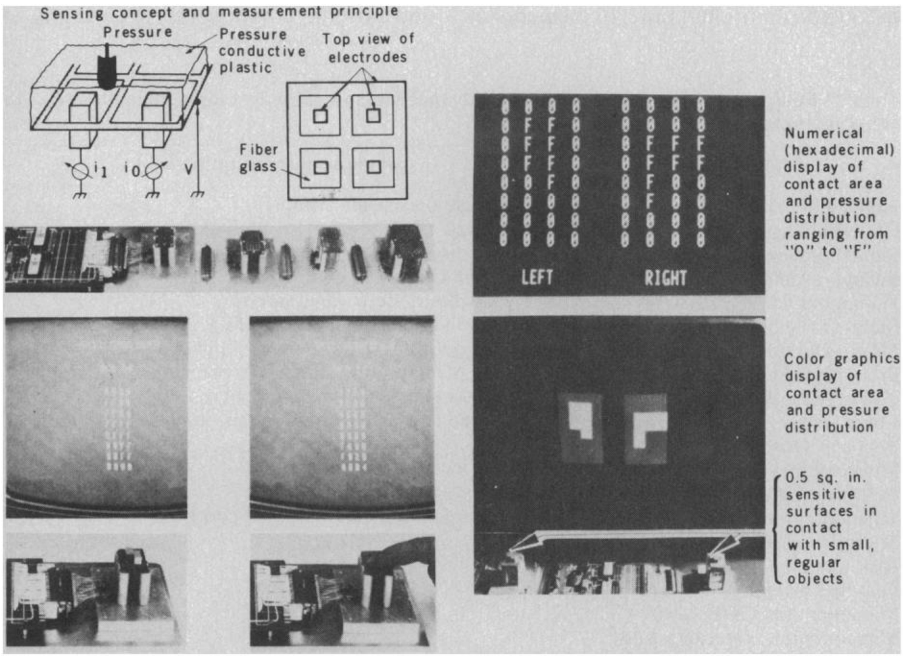

Fig. 5. Window touch sensor with display of numeric and color graphics.

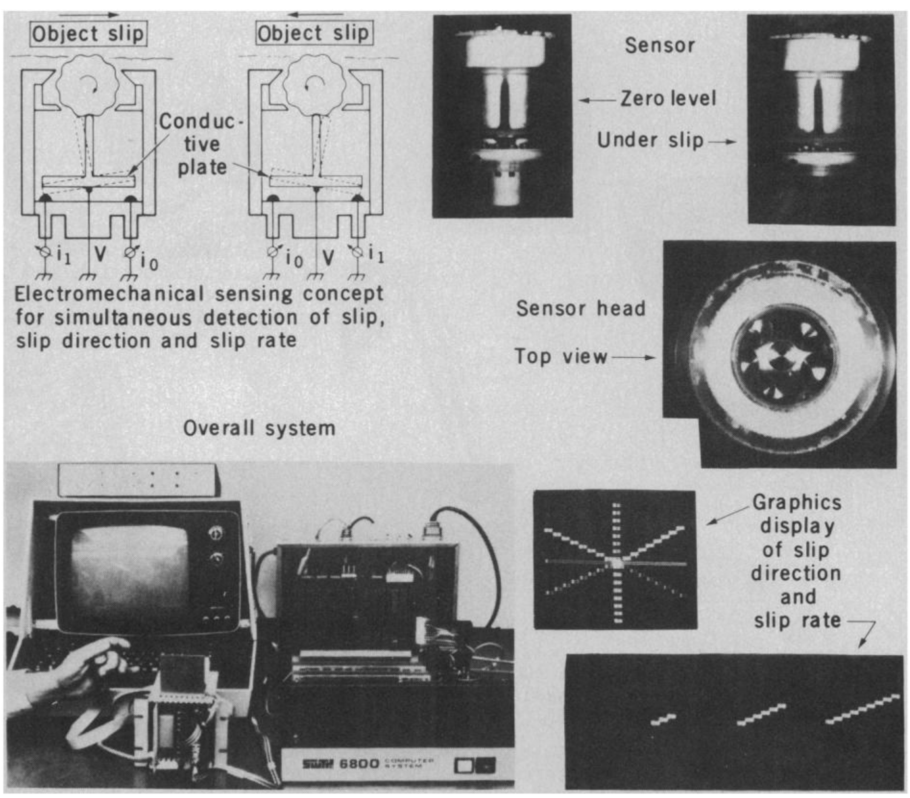

Fig. 6. Omnidirectional slip sensor with display of slip rate and direction.

Touch and Slip Sensors

Touch sensors are intended to simulate the sense of touch, and hence can be called "artificial skin". Two types of touch sensors, with different area and pressure resolution and different kinds of signal-generating electronics, have been developed at JPL. Both types are multipoint proportional sensors and utilize pressure-conductive plastic as the sensing element.

The first type of touch sensor is based on a "sandwich" concept in that it is built from two linear arrays of thin, flat, flexible electrodes that intersect diagonally and are separated by a thin pressure-conductive material. The center of a "sensitive cell" is defined by the intersection of two diagonally running electrodes. The lateral dimensions of a cell are defined by the width and separation of the electrodes. Hence 2-mm-wide electrodes, separated laterally by 2 mm, define 4 by 4 mm sensitive-area units centered at the diagonal intersections of two electrodes.

The second type of touch sensor is based on a "window" concept. The individual sensitive cells are defined by individual electrodes and by a common ground surrounding all individual electrodes and forming a matrix pattern of small square windows (Fig. 5). In this arrangement, the size of a window equals the size of the sensitive-area unit, which, in turn, defines the contact or pressure area resolution of the sensor. The electrodes are etched on a fiber-glass board. Current flows through a sensitive cell between the common ground and the individual electrode of the cell when the conductive material covering the cell is pressed. In the smallest configuration, this touch sensor has 32 sensitive cells arranged in a four by eight matrix pattern over an area 12 by 24 mm. Under ideal conditions, each cell can measure contact pressure between 2 and 50 N/m^2. Thus this type of sensor can recognize intensities over a particular contact area pattern. The sensor data are digitized, handled by a microprocessor, and displayed in numeric or graphic format on a TV monitor (Fig. 5). The real-time graphics display can be black and white or color.

Two types of slip sensors have also been developed at JPL. Both sensors are omnidirectional in that they detect slip irrespective of the direction of the slip. The omnidirectional slip detection is achieved by the use of a sphere as the mechanical rolling element of the sensor.

The first type of slip sensor detects only the fact of slip. In this sensor, magnetic pins are embedded in a nonmagnetic sphere held with a bearing in front of a magnetic pickup. When the sphere is rotated, the pins move past the pickup. If an object is pressed against the sphere, any slippage of the object turns the sphere and generates electrical pulses through the magnetic pickup. The pulses drive a light-emitting diode display showing the fact of slip.

The second type of slip sensor detects not only the fact of slip, but also its direction and rate (Fig. 6). This sensor utilizes a circular conductive plate attached to a needle. There are 16 electrical contact points distributed evenly around a circle under the plate. The needle contacts a sphere that has small dimples distributed over its surface in an irregular pattern. The sphere is supported with a bearing. If an object is pressed against the sphere, any slippage of the object turns the sphere. The rolling sphere oscillates the needle, causing the circular plate attached to the needle to touch one of the 16 electrical contact points, thus closing the corresponding circuit. Which of the 16 contact points is touched depends on the direction of the oscillation of the needle, which, in turn, depends on the direction of the roll of the sphere. Thus, this type of sensor can detect slip in 16 directions. The output signals of the sensor are pulses distributed over 16 channels that signify the direction of the slip. Since the distribution of the dimples over the ball is irregular, the oscillation of the needle generated by a directional roll of the ball is within 25° to 35° (cone angle). This causes pulse signals in two to three adjacent channels, even for slippage of an object in a constant direction. The pulse signals are handled by a microprocessor, averaged, and displayed as compass vectors on a TV monitor.

The touch and slip sensors are currently in breadboard form. It is felt that more breadboard work on these sensors is needed before a technically meaningful integration of mechanical hand, sensor, and control can take place.

Man-Machine Interface

Enhancement of man-machine interface is pursued in three major areas at JPL: graphic display of sensor information, voice communication with the control system, and kinesthetic coupling between operator and mechanical arm.

Graphic display of sensor information is handled in real time by a microprocessor (*25*). Proximity, force-torque, and touch and slip sensors generate multidimensional data that can impose a heavy perceptive and cognitive workload on the operator in both manual and computer control modes. Recently, event-driven displays of sensor data have been developed that provide a convenient means for focusing the operator's attention on control goals (*19*). The implementation of event-driven displays requires the development of real-time algorithms (based on predefined control events) for coordinating and evaluating sensor data and for driving an appropriate display that conveys information to the operator when the event occurs.

The development of event-driven displays requires the consideration of various technical and human problems. These include (i) integrating different displays into a coherent working format, (ii) determining how much and what kind of detailed information the operator should be exposed to in addition to the event information, (iii) determining how the operator should control the displays, and (iv) making the display-driving algorithms flexible so that changes in control goals or subgoals can be easily accommodated by simple changes in the algorithmic parameters to match a given control task.

More advanced versions of event-driven displays have also been developed in which changes in sensor data automatically effect changes in both display formats and display parameters, matching the particular information required for manipulator control at different phases of the task (*27*). The automatic changes of display modes or parameters follow a state-transition diagram by means of which the characteristic or critical event states of a given task are mapped.

Voice communication with the control system has been implemented by employing a discrete work recognition system supplied by Interstate Electronics. It is a trainable acoustic pattern classifier that produces a digital code as an output in response to an input utterance. The voice recognition system is implemented in a dedicated minicomputer as part of the mini- and microcomputer network of the JPL advanced teleoperator development laboratory (Fig. 1). The vocabulary

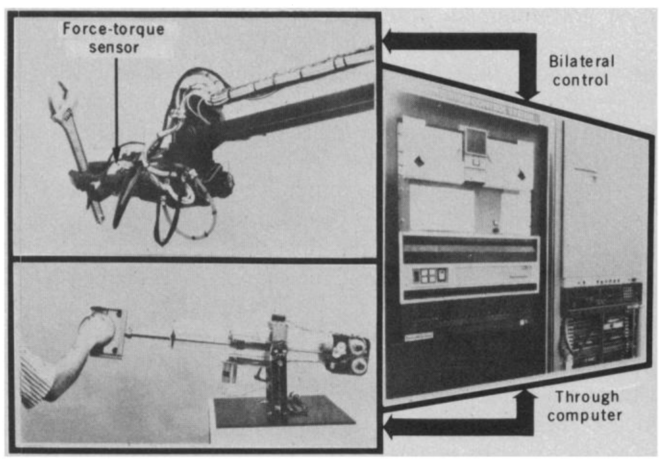

Fig. 7. Six-dimensional force-reflecting position hand controller.

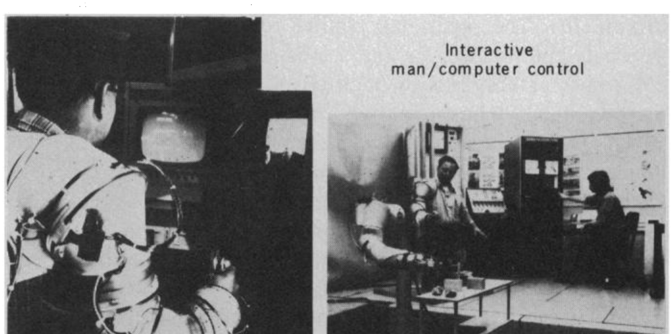

Fig. 8. Setup for computer- and sensor-aided performance experiments.

can comprise up to 400 words, and the words can be arranged in an appropriate control/command syntax. The voice recognition system is used to control displays and manipulator motion (*21*). For example, when the operator's hands are busy with manual control tasks, he can effect changes in TV and other displays by voice command. A voice synthesizer can convey critical messages verbally from the control computers to the operator.

Also under consideration is the installation of a connected speech recognition system that may further enhance vocal communication between operator and control computer. This type of speech recognition could be useful for communicating with an "intelligent" data base, aiding the operator in updating or modifying control procedures during complex tasks.

Conventional communication between man and machine is indirect. Normally, it requires manual or tactile input from man to machine, and some visible output from machine to man. This indirect communication often renders man-machine interaction inefficient and inflexible. Voice communication with machines offers many potential advantages. One can benefit from the physical characteristics of natural language communication: physical separation and physical mobility are permitted for man and machine when the speech input/output system is used for communication between the two, and the communication capacities of the vocal/audio channels are within reasonable reach most of the time. Also, multimodal communication offers greater versatility.

Kinesthetic man-machine coupling has recently been developed in the form of a general-purpose, force-reflecting position hand controller, a six-dimensional control device that can be back-driven by forces and torques sensed at the base of the end effector of a remotely controlled mechanical arm (Fig. 7). The device serves a general purpose in that it does not have any geometric or kinematic correspondence with the mechanical arm it controls and from which it is back-driven (*30*). The positional control relation between this device and a mechanical arm is established through real-time mathematical transformation of joint variables measured at both the control device and the mechanical arm. Likewise, the forces and torques sensed at the base of the end effector are resolved into appropriate hand-controller joint drives through real-time mathematical transformations to give the operator's hand the same force-torque "feeling" that is felt by the end effector on the remote mechanical arm. For example, an operator working with a wrench held by the remote mechanical hand will experience nearly the same kinesthetic feeling as if he held the wrench by his own hand. The complex bilateral and real-time control computations are performed by a dedicated minicomputer at an update rate of 50 hertz.

The force-reflecting position hand controller is a fundamental development tool. Researchers are using it to advance the state of the art in dexterous remote manipulator control that requires force feedback; also, it is aiding in the investigation and evaluation of critical performance parameters related to kinesthetic man-machine coupling in remote manipulator control.

Table 2. Performance data for computer-aided and manual control guided by proximity sensor information.

Control mode	Mean time of ten experiments (seconds)	Positioning accuracy (standard error, cm)
Fully human		
With forward sensors	8	0.95
With downward sensors	8	0.85
Computer-aided		
With forward sensors	4.6	0.25
With downward sensors	2.7	0.2

Performance Evaluation

To date, performance evaluation experiments have concentrated on sensor and computer-augmented manipulator control (Figs. 4 and 8) (*17, 31-33*). The experiments have shown that proximity-sensor information can replace or supplement some critical part of the visual information required for control. Control tasks that cannot be performed with visual information alone can be performed with proximity-sensor and visual information combined. In general, operators are more comfortable with proximity-sensor information than with visual cues alone. With proximity-sensor information, it is possible that some of the visual work load is lessened, reducing work tension in the operators to some degree. Furthermore, the experiments have demonstrated that automated, proximity-sensor-based control can result in faster, easier, safer, more precise, and more economical operation (Table 2). But the operator must have a clear a priori notion about the expected outcome of an automated proximity control loop as applied to a given task before he uses that loop.

Force-torque sensor/computer control experiments led to the following conclusions: (i) in manual control, the rate mode provides a better performance than the position mode does. However, a fine-control position mode (that is, one in which a multiple-turn position controller is used) should also be tried out for touchdown control with force-torque feedback. (ii) Computer force-torque feedback provides a nearly linear relation between load transfer to jigs, rate of motion, and preset force-torque threshold values for stop under the investigated motion and load conditions. Furthermore, automated computer force-torque feedback provides for a highly repeatable performance for load transfer at contact. This is in contrast to the performance variations observed in manual control as a function of training, learning, and other human factors. (iii) Force-torque information is very complex since it must be viewed together with the task geometry. Therefore, the graphic display of force-torque information should be enhanced or condensed to ease the operator's perceptive and cognitive work load.

Control experiments have also shown that a realistic performance evaluation requires the simultaneous consideration of at least three somewhat overlapping performance measures: (i) the binary categories of "success" or "failure" for evaluating the effectiveness of control; (ii) the combination of "accuracy" and "time" for evaluating the quality of control; and (iii) the integrated "consumption of applied resources" for evaluating the cost of control.

Conclusions

Advanced teleoperator technology invites new and challenging developments in many areas of applied science and engineering: mechanisms, sensors, controls, computer application, automation, man-machine interface, and system design. Many different kinds of hardware and software components will contribute to the advancement of teleoperator technology. In particular, it is desirable and feasible to introduce more automation components into teleoperator systems. The efficient teleoperator devices of tomorrow will probably have semiautonomous capabilities.

Space technology, undersea operations, mining, nuclear or other high-radiation laboratories, and rehabilitation engineering all have a common interest in advancing the state of the art in teleoperator technology. New developments in teleoperator technology may also have a substantial economic impact on industry (*34*).

There is much reason to believe that the hand has been a major determining factor in human evolution. Together with the human brain and binocular vision, the human hand has enabled us to be tool-makers and tool users, and to explore, manipulate, and change the physical environment. Advancements in teleoperator technology will help extend this essential human capability and function to dangerous or inaccessible places.

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Expert and Novice Performance in Solving Physics Problems

Jill Larkin, John McDermott, Dorothea P. Simon, Herbert A. Simon

Experts solve complex problems considerably faster and more accurately than novices do. Those differences are commonplaces of everyday experience, yet only recently have we begun to understand what the expert does differently from the novice to account for this superiority.

The magic of words is such that, when we are unable to explain a phenomenon, we sometimes find a name for it—as Molière's physician "explained" the effects of opium by its dormitive property. So, we "explain" superior problem-solving skill by calling it "talent," "intuition," "judgment," and "imagination." Behind such words, however, there usually lies a reality we must discover if we are to understand expert performance.

One label often applied to persons skillful in solving physics and engineering problems is "physical intuition." A person with good physical intuition can often solve difficult problems rapidly and without much conscious deliberation about a plan of attack. It just "occurs to him (or her)" that applying the principle of conservation of momentum will cause the answer to fall out, or that a term in kinetic energy can be ignored because it will be small in comparison with other terms in an equation. But admitting the reality of physical intuition is simply the prelude to demanding an explanation for it. How does it operate, and how can it be acquired?

In this article, we undertake to describe what is known about human ex-

The first, third, and fourth authors are members of the Psychology Department, and the second and fourth authors of the Computer Science Department, Carnegie-Mellon University.

0036-8075/80/0620-1335$02.00/0