NASA SP-5070

AN AEC-NASA TECHNOLOGY SURVEY

TELEOPERATOR CONTROLS

TECHNOLOGY UTILIZATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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An AEC-NASA TECHNOLOGY SURVEY

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FOREWORD

This book is the second by the authors relating to Teleoperators and Human Augmentation. It is a survey of an emerging facet of control technology which, when adopted by industry, will have a profound effect upon the development of new products and new processes. The technology of sophisticated control—particularly the cybernetic interaction between man, computer and versatile machines—is important in the fields of nuclear energy, in our investigation and use of the ocean's resources and in space exploration. Further applications of teleoperator systems will occur in industry, urban services, and even agriculture. Teleoperator control is becoming an essential part of our scientific-engineering-industrial basis for a more advanced society, one in which knowledge and technology—rather than nature and man—can be exploited.

The sources of teleoperator technology are found in recent work in biomechanics, computer science, and the remotely operated equipment used by the AEC and NASA. Teleoperator systems augment and extend man—they do not replace man. Man is always in the control loop, a characteristic that distinguishes the teleoperator system from automation.

It is hoped that this book, describing the current development of teleoperator control theory and hardware, will stimulate further refinements in this fascinating symbiosis between man and machine. New approaches are needed if society is to fully realize the benefits of modern science. The virtually unlimited energy made available by nuclear science, the new level of sophistication being achieved by our chemistry and physics, our earth sciences and life sciences—all this coupled with the ability to augment man through teleoperators, will hopefully propel us toward a society in which man can at last have time and resources to think and act in new directions and new dimensions.

Glenn T. Seaborg

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Chapter 1

INTRODUCTION

A teleoperator is a general-purpose, dexterous, man-machine system that augments man by projecting his manipulatory and pedipulatory capabilities across distance and through physical barriers into hostile environments. A manipulator that fabricates radioactive fuel in a hot cell is a teleoperator because it transmits man's dexterity through the hot-cell wall into the lethal environment. Teleoperators can also extend man's hands to the Moon and planets before he can make the trip himself (Table 1). An artificial limb is considered a teleoperator because it augments an amputee by restoring a part of his lost dexterity—the lost limb is in effect a barrier to normal operation.

Man is nearly always in the teleoperator control loop. In contrast, clock-radios and computer-controlled machine tools are preprogrammed machines, not teleoperators, because man is never in the loop on a real-time basis. Neither are robots teleoperators. Robots operate autonomously and sometimes (in science fiction, at least) counter to man's interests. The man-machine relationship in the teleoperator is essentially *symbiotic*; that is, mutually beneficial. Man needs the machine's strength and resistance to hostile environments, while the machine depends upon man's brain and dexterity.

The adjective "dexterous" in the definition of the teleoperator excludes the great host of nondexterous man-machine systems that surround us. To illustrate, the automobile becomes a part of a man-machine system when the driver brings it to life with the ignition key; yet the automobile cannot manipulate anything for all its other attributes.

In metal-working plants or construction jobs, and on many production lines, one sees man-machine systems that pick up, position, and otherwise manipulate objects and materials. We prefer to exclude these single-purpose mechanical hands and fingers from the class of teleoperators by adding the adjective "general-purpose" to the definition. Teleoperators should be thought of as extenders and augmenters of man; and man is a general-purpose, versatile creation.

SCOPE OF THIS SURVEY

In a previous survey,[1] we have described the ascendancy of teleoperators and how they are already expanding man's environmental frontiers as his

Table 1 The Four Major Classes of Teleoperators

Teleoperator Type	Characteristics	Typical Applications
Manipulators (Fig. 1)	Mechanical analogs* of human arm and hand. May be fixed or attached to vehicles.	Common in radioactive hot cells, undersea research craft, and similar "hostile" environments. Many thousands now in use.
Prosthetic and orthotic devices (Fig. 2)	Mechanical analogs* of human arm and hand, attached directly to the body.	Artificial limbs replace the natural limb, while orthotic devices aid damaged or weakened members. In common use.
Man amplifiers (Fig. 3)	Mechanical analogs* of entire or a large portion of the human body. Generally, these are exoskeletal machines that fit around the body somewhat like a knight's armor.	Handling heavy loads, particularly in military and undersea environments. Still in development stage.
Walking machines (Fig 4)	Mechanical analogs* of human legs controlled by operator directly (not preprogrammed).	Locomotion over rough terrain unsuited to wheels. Non-preprogrammed types still being developed.

*The analogs are generally not exact. They usually have many fewer degrees of freedom than a human; although they often incorporate degrees of freedom unknown to humans, such as joint extension.

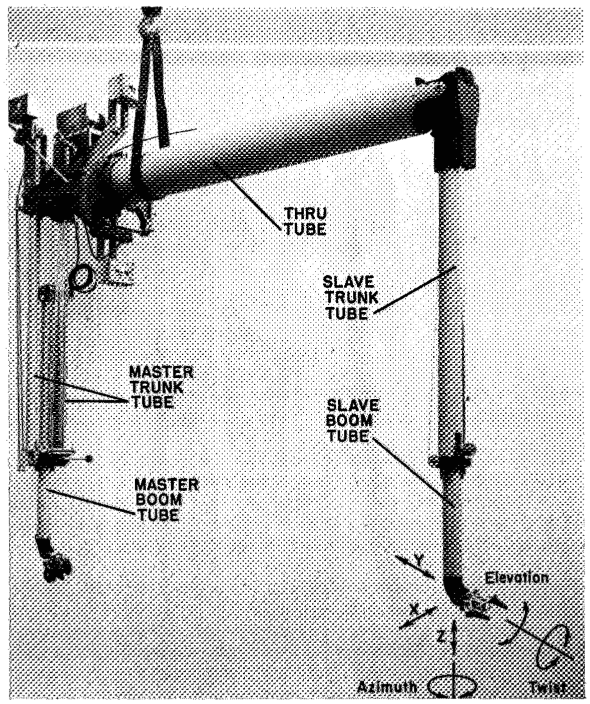


Figure 1 *A CRL Mod-8 mechanical master slave. The motions of the master arm and hand are communicated to their slave counterparts through control cables. Compare with Fig. 6. (Courtesy of Central Research Laboratories.)*

Figure 2 *A pneumatic artificial arm. (Courtesy of E. Murphy, U. S. Veterans Administration.)*

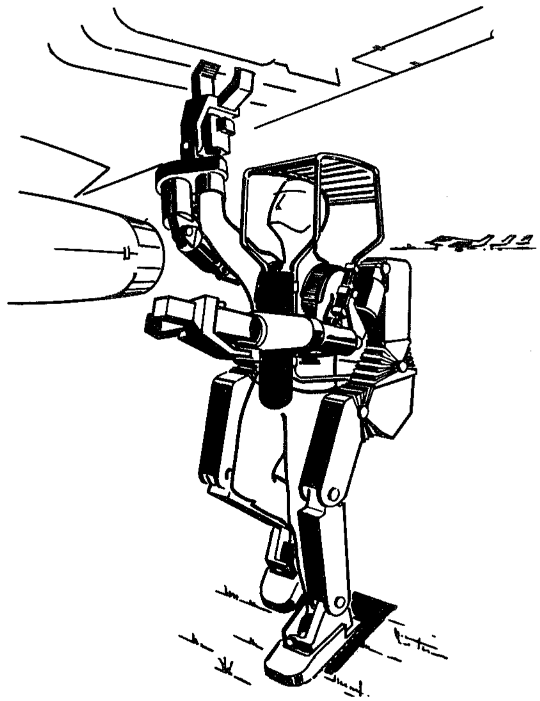


Figure 3 *Artist's sketch of the General Electric/Department of Defense powered man amplifier (Hardiman I). (Courtesy of R. S. Mosher, General Electric Co.)*

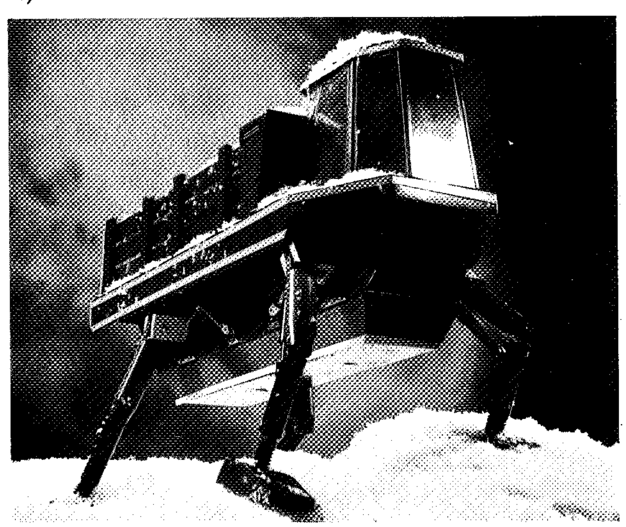


Figure 4 *Artist's concept of the General Electric/Department of Defense Walking Truck. (Courtesy of General Electric Co.)*

proxy and precursor. In this survey, we focus on the subject of teleoperator control.

Flexible, responsive, sensitive control is a keystone of successful teleoperator design. But because man and machine are linked so intimately in the teleoperator, teleoperator control engineering is not as well developed as it is, say, in missile control, where man is usually not in the loop. Man with his strengths, his weaknesses, his nonlinearity, and his manifest complexity makes teleoperator control a challenging field.

No well-defined body of theory and practice bears the label "teleoperator control." The lore and literature of teleoperator control consist of bits and pieces from many disciplines. The Atomic Energy Commission (AEC) has pioneered the control technology of mechanical and electrical master-slave manipulators,* especially at its Argonne National Laboratory (ANL). The National Aeronautics and Space Administration (NASA) has contributed to teleoperator control in two quite different ways: (1) the theory of manual control as used in describing the piloting of aircraft; and (2) the use of computers as aids to human operators in situations where significant time delay exists (predictive or preview control) and where control tasks are complex (supervisory control). The Department of Defense (DOD), like NASA, has studied manual control in depth in connection with aircraft. It has also sponsored considerable research and development work on walking machines and man amplifiers. Further, in connection with M.I.T.'s Project MAC (Machine-Aided Cognition), DOD has investigated computer-controlled manipulators. To the government-sponsored work must be added centuries of hardware developments in the fields of prosthetics and orthotics, where practical techniques have been emphasized more than theory. Assimilating these bits and pieces, we can construct a comprehensive though incomplete description of teleoperator control. This integration is a major objective of this survey.

The titles of Chapters 3 through 6—the cornerstone technical chapters—may be paraphrased as: control theory, the man-machine interface, control hardware, and displays. Only the chapter on displays is deliberately restricted; the subject is so broad that we can deal only with those aspects that relate to teleoperator control.

RESUME OF TELEOPERATOR DESIGN PRINCIPLES

From hot-cell master-slave to walking machine, teleoperators vary widely in physical configuration. Nevertheless, generalization is possible: Fig. 5 illustrates how a teleoperator can be disassembled into ten subsystems; all united by the mutual interchange of control signals, power, physical

*See Table 3, Chap. 2, for manipulator definitions.

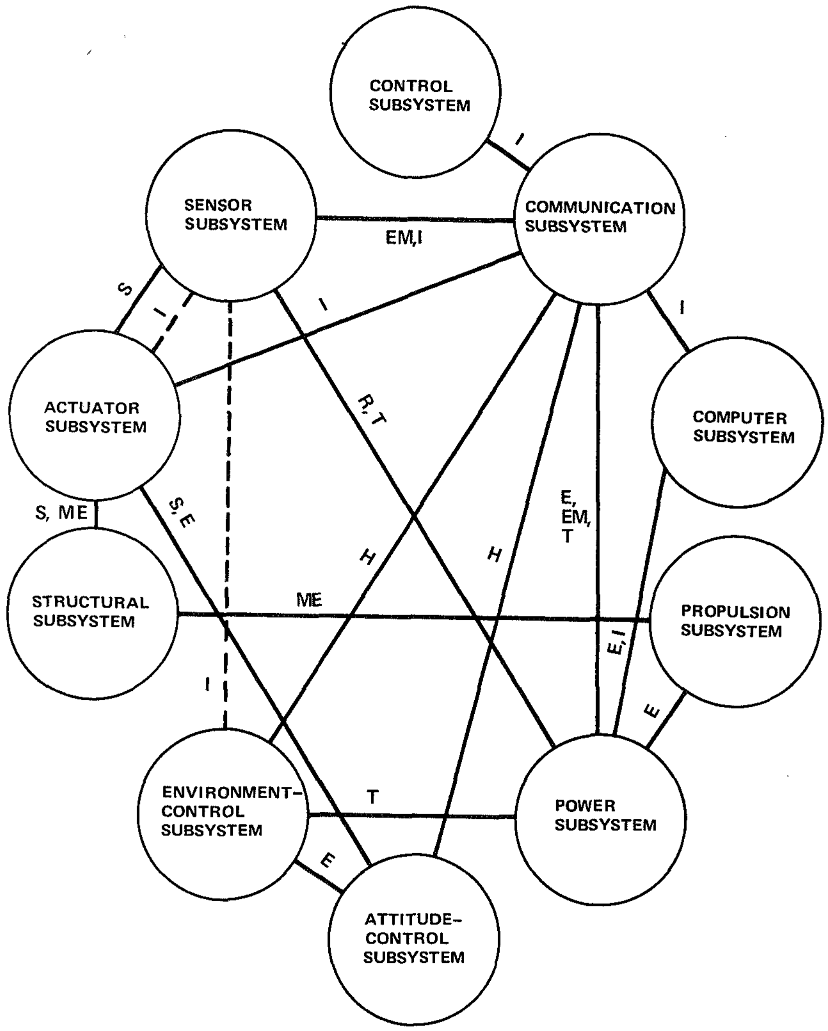


Figure 5 *Teleoperator subsystems, showing some of the important interfaces. S = spatial, E = electrical power, ME = mechanical, T = thermal, I = information, R = radiative, EM = electromagnetic. Dotted lines indicate local control loops that bypass the central control subsystem; viz., thermostat thermal control.*

structure, and other "forces" at their interfaces. Except for the control subsystem, which will be covered in depth in this book, we now summarize the major facets of subsystem design as detailed in Ref. 1.

The Actuator Subsystem. This subsystem carries out the manipulations, walking motions, and other dexterous activities ordered by the human

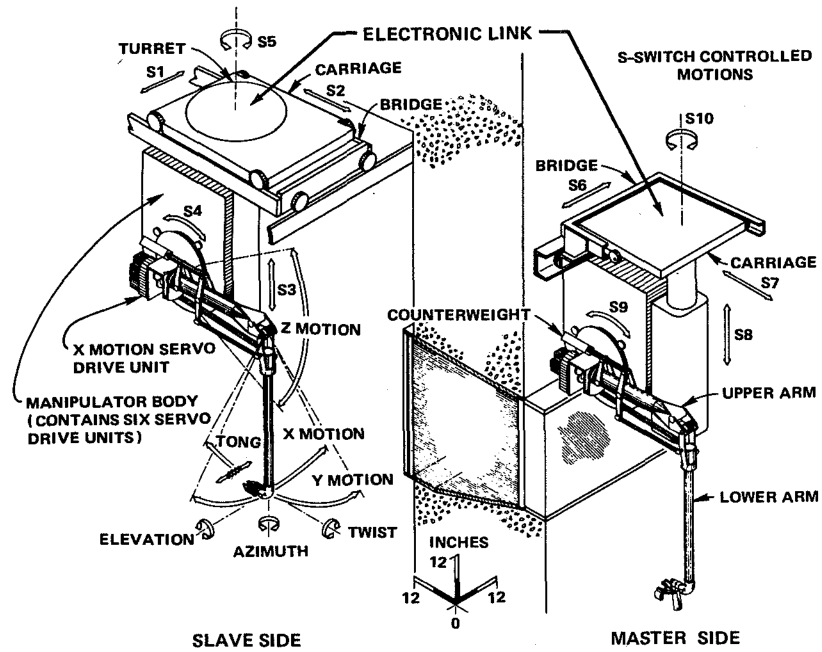


Figure 6 *Installation diagram for the ANL E3 electric master slave. Motions of the master control arm and hand are communicated to the slave-side actuators electronically. (Courtesy of Argonne National Laboratory.)*

operator. The actuator subsystem is the *effector* portion of the teleoperator. The slave arms and hands of the familiar master-slave manipulators comprise a typical actuator subsystem. The purely mechanical manipulators, where man activates the slave arms and hands with cables somewhat analogous to puppet strings, are the most common. Electrohydraulic actuators are favored for underseas work and in walking machines and man amplifiers because of their strength per unit volume. ANL has built several varieties of electrical master-slaves for nuclear work (Fig. 6). Many switch-controlled electric manipulators are now in service in many fields (Fig. 7). These differ from the electric master-slaves in that force feedback is not present.

The Sensor Subsystem. The sentient portion of the teleoperator may see, feel, hear, or otherwise sense the environment, giving the operator rapport with transactions in the working area. More than any other subsystem, the sensors enable man to project himself across distance and through barriers to the spot where his appendages are partially duplicated in metal, plastic, and other inorganic media. Television cameras and direct viewing are common in teleoperator work because sight is almost always the most useful of man's senses in manipulation. Force feedback and tactual sensation are the next most useful, particularly in assembly of tight-fitting

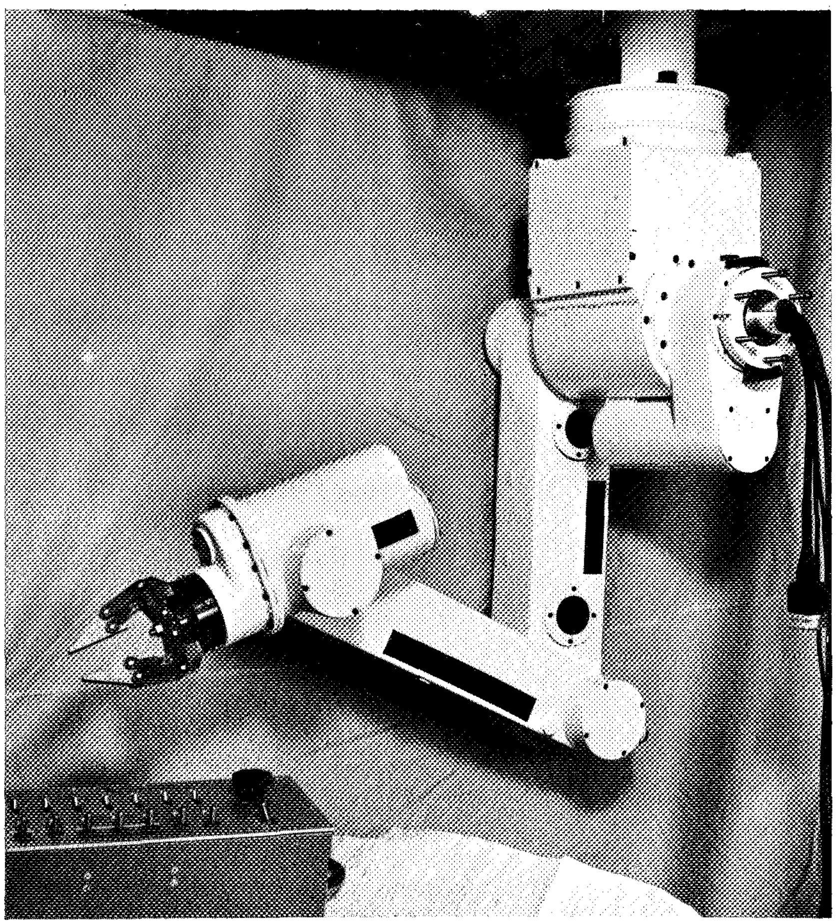


Figure 7 *A typical switch-controlled electric unilateral manipulator. (Courtesy of R. Karinen, Programmed and Remote Systems.)*

parts and similar operations. Some force feedback exists in mechanically connected manipulators, such as the omnipresent mechanical master-slaves, where cables transmit forces both to and from the operator. The ANL electrical master-slaves and some electrohydraulic teleoperators employ servos to provide force feedback. Looking to other possibilities, microphone pickups, sonars, infrared cells, and gyros are only a few ways in which information about the working area can be transmitted back to the operator. Some sensors are nonanthropomorphic—Moiré-pattern tactual sensors, for example—and the operator has to learn how to interpret this unnatural feedback. In the control subsystem, all kinds of feedback are melded into a presentation or display (not necessarily visual) that helps the operator identify himself with the task and its environment.

The Communication Subsystem. Wires, electromagnetic links, and mechanical linkages, form the nervous system of the teleoperator. Feedback information from the sensor subsystem speeds back to the operator via the communication subsystem. Likewise, his commands are transmitted in the opposite direction to the actuator subsystem. In the simple switch-controlled unilateral manipulators, only a narrow bandwidth is needed to transmit the operator's commands. At the other extreme, television feedback requires a very wide bandwidth. At a more primitive level, the two communication links in a mechanical master-slave are those created by the push and pull of the control linkages and direct viewing of the target through, say, a hot-cell window.

The Computer Subsystem. Man often needs help in controlling a teleoperator. Signal time delay, task complexity, and human response time bring computers into the picture. Computers can make calculations and predictions that improve the operator's decision making capability. Computers can also operate using fast, sophisticated subroutines that relieve the operator of some of the routine operations, such as the stowing of a submersible's manipulator. In more advanced teleoperators, computers will be able to generate displays from the incoming feedback data. When we discuss teleoperator computers, we are generally talking about the future. While digital computers have been studied for space and undersea applications, the only operational teleoperator computer is an analog computer employed by the Navy's Deep Sea Rescue Vehicle (DSRV) for controlling its manipulator arm during a few routine operations. In the realm of experiment, NASA and DOD have supported research on manipulators controlled by digital computers at M.I.T., Case Western Reserve, and elsewhere.

The Propulsion Subsystem. Motor-driven wheels, rockets, screws, and the leg-like parts of exoskeletons serve to propel teleoperators from place to place. Rockets and gas-jet propulsion units have been proposed for orbital operations utilizing teleoperators. Beneath the ocean, screws and water jets are already used for research and military submersibles carrying manipulators. On land, a variety of wheeled and tracked manipulator-equipped vehicles have been constructed for nuclear rescue and cleanup work.

The Power Subsystem. Man himself provides the power in mechanical master-slaves and in some artificial limbs. Wherever commercial power lines go, they are a ready source of power. In space and underseas, power sources usually have to be carried along with the teleoperator. Chemical units (fuel cells and internal combustion engines), batteries, and nuclear power sources have been suggested. In general, the teleoperator operates from the power supply of the vehicle or building where it is attached. The so-called externally powered artificial limb is an exception; it requires a special battery or source of compressed gas.

The Attitude-Control Subsystem. To stabilize and maintain the spatial orientation of a teleoperator, particularly of space vehicles, submersibles, and walking machines, a variety of jets, screws, docking arms, and balancing devices has been designed. In space and under the sea, where vehicles "float" freely, reaction engines are almost essential, although magnetic attitude control subsystems acting in conjunction with the Earth's field are feasible for small Earth satellites. Walking machines and man amplifiers with legs, of course, use their feet for maintaining balance and an upright position. The attitude control subsystem also includes the sensors that measure attitude, such as horizon sensors, gyroscopes, and even man himself through his sense of balance.

The Environment Control Subsystem. This subsystem maintains proper temperatures, atmospheres, radiation levels, etc. within the teleoperator. Radiators would be employed for dissipating excess heat in outer space; in marine applications, seawater is an excellent heat sink. Vehicle atmospheres for astronauts and their watery counterparts are either carried along and expended, or recycled. Shields protect the teleoperator and its operators from radiation (from space or a nuclear power plant) and meteoroids.

The Structure Subsystem. The structure subsystem unites and supports the other subsystems. In teleoperators, of course, the system-as-a-whole is often divided physically by an environmental barrier or by great distances. When the operator is safe on Earth or on a surface ship, the manipulator-carrying vehicles may be open to vacuum, seawater pressure, radiation, smoke, or whatever constitutes the hazardous environment. When man goes along, he must be protected by space-capsule walls, massive hulls, and the like. Many of the mobile, terrestrial teleoperators are simply built like tanks, trucks, or bulldozers. The structures of the teleoperator arms and legs themselves usually mimic the human body in form but generally employ external rather than internal skeletons. Man amplifiers, for example, are patterned after the insect world because they fit around the human operator like a beetle's hard carapace.

In the structure subsystem we see best the many facets of this class of man-machine systems we call teleoperators. The actuator terminals mimic man, but the bodies are heavy shells or skeleton-like: they are wheeled or many-legged, hung on hot-cell walls, or mounted on tank bodies. At the operator-machine interface, we again find great variety, for man's senses are manifold and there are a multitude of ways in which he can bring life to his ersatz hands and arms, be they on the Moon or in some dark, abyssal ocean trench. The rest of this book describes how man controls this most versatile kind of machine.

Chapter 2

A SKETCH OF THE CONTROL SUBSYSTEM

ESSENCE OF CONTROL

To control his machines man acts primarily as a goal-setter and an error corrector. He decides what he wants the machine to do; he plans the strategy; he gages the machine's deviation from desired performance; and he manipulates the machine's controls in a way that reduces the error. He does this when he steers a car along a winding road and when he picks up a sample of lunar soil with a teleoperator hand from a distance of a quarter-million miles. These words and the control schematic shown in Fig. 8 actually oversimplify the situation. Any control system that counts a human being

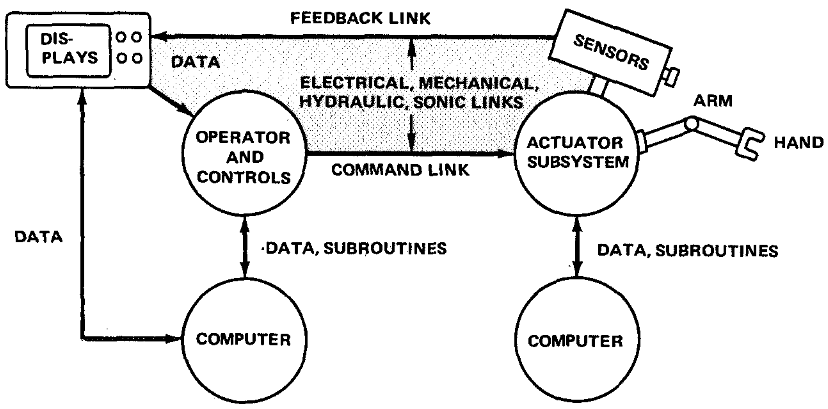


Figure 8 *The teleoperator control loop (shaded), with computer support for supervisory control, display generation, and direct support of the operator.*

among its elements is complex and difficult to describe scientifically because man himself is so complex and difficult to describe.

Why, then, admit man to the teleoperator control loop? Machines can certainly detect their own errors and correct them; autopilots and home heating plants do this very nicely. The reason for man's presence stems from his ability to set strategy and to deal with the unexpected—those situations we cannot preprogram into a machine's memory. Man is an adaptive creature; and, if teleoperators are to be the extension of man, they must be adaptive also. To illustrate: Could a pure machine uncomplicated by man's presence figure out how to repair a ruptured oil pipeline far out on the continental shelf?

In principle, the answer to the foregoing question is "yes." Adaptive machines, machines that learn from experience, can and have been built. They are true robots. Today's robots, however, cannot approach man's adaptability, versatility, and intelligence. It would take many ruptured pipelines before a robot learned how to fix them. For decades, at least, man-operated teleoperators will reign supreme in those hazardous and distant spots where man prefers to send machine proxies.

Most extant teleoperators are "pure" man-machine systems; that is, man is *always* in the control loop. As teleoperator technology progresses, though, preprogrammed subroutines are being added to relieve the operator of those wearisome, repetitive tasks that can be done better by machines. A very simple and basic preprogrammed subroutine is one which stops teleoperator arm motion when limit switches indicate that self-inflicted damage is imminent. Most complex machines include similar localized reflex control arcs that intrinsically react faster than man. Subroutines are also extremely useful in space operations—say, lunar exploration—where there is significant signal time delay between operator and teleoperator hands. Such subroutines, which are intrinsic to Sheridan's and Ferrell's *supervisory control* approach,[2] do not add to a teleoperator's intelligence or adaptability, but they improve overall effectiveness considerably, especially where time delays are large. In principle, then, a continuous spectrum of teleoperators exists between the pure, man-always-in-the-loop extreme to the completely preprogrammed, dexterous, general-purpose machine possessing only an ON-OFF switch, in other words, a *robot*. As technology progresses, we may expect to see teleoperators move toward the robot end of the spectrum.

The ingenuity of man and his passion for making machines that emulate himself should not be discounted. The future may soon see the addition of adaptive or artificially intelligent subroutines to teleoperators. At first, some of the simpler, more routine decisions might be machine-made. Eventually, both preprogrammed and adaptive subroutines might be added until man could say to a machine, "Go and explore the galaxy for me." Philosophically speaking, the teleoperator may be a transitional man-machine system that presages generations of machines that are man-like, man-directed, man-serving, and yet self sufficient save for a few spoken commands from their masters. This would be the ultimate man-machine world that Landers calls the *dybosphere.*[3]

The moral behind these projections of what may come (and sooner than we expect) is that the relatively crude switch and servo controls of contemporary teleoperators are merely harbingers of a man-machine partnership that will be effected by the spoken word, the gesture, and the nuances that command the best servants.

MAKEUP OF THE CONTROL SUBSYSTEM

At the core of the control subsystem is the human operator (Fig. 9). Toward him flow feedback data that describe the positions and velocities of the teleoperator's hands, arms, and other actuators as well as the objects being manipulated. From him flow the commands that will reduce (hopefully) the error he perceives in teleoperator performance. The human brain is

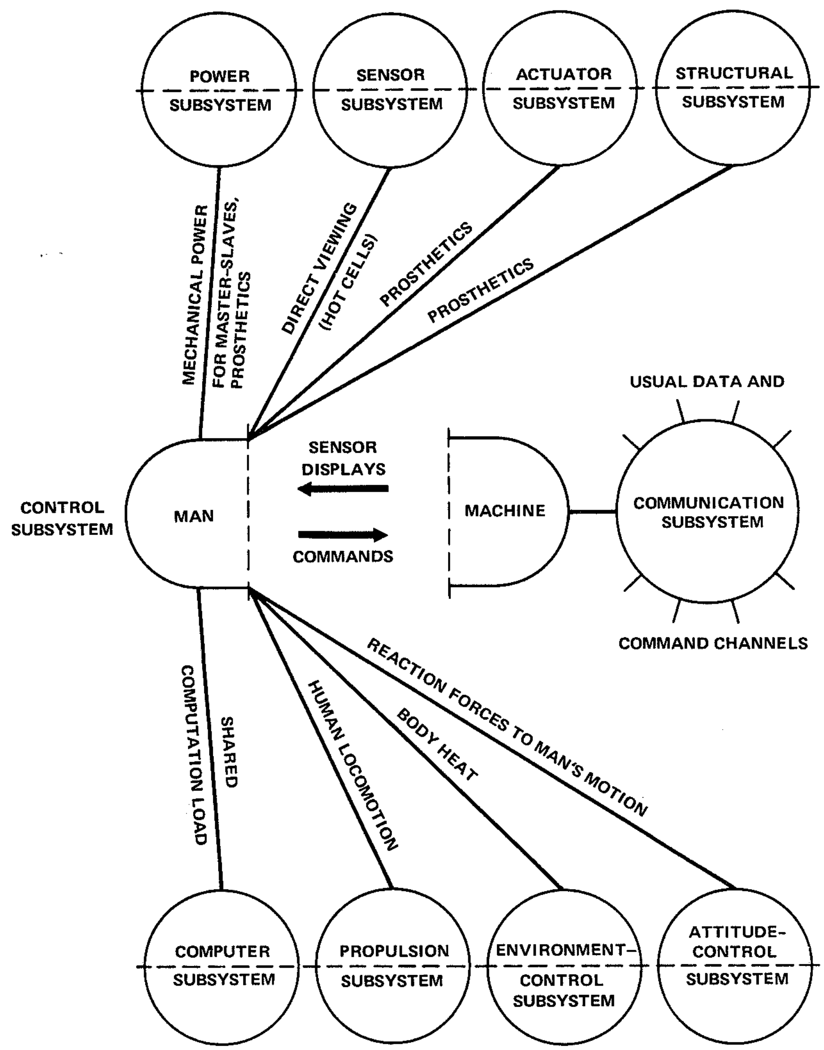


Figure 9 *The man-machine interface is penetrated primarily by display data and commands, but man also interacts with almost every subsystem in some way.*

the goal-setter and the error computer, planner, and decision maker, although a computer may supplement some brain functions.

Two man-machine interfaces are of paramount importance. First, feedback information from the machine part of the teleoperator must be "read into" the brain so that a performance error can be computed. Current terminology calls the device that translates machine sensor readings into signals comprehensible to the brain a *display* (Chap. 6). A display may be simply a faithful television view of the scene or it may be a symbolic display, such as a meter indicating the grip force exerted by the teleoperator hand. The second critical interface separates man from the teleoperator actuators, as well as other teleoperator subsystems under the operator's direct control. Man's commands to his machine partner stream through his central nervous system to his arms, hands, eyes, tongue, and other parts of his anatomy that can create mechanical, sonic, and electrical signals. These signals cross the man-machine interface and activate *controls* that convert them into commands comprehensible to the rest of the teleoperator (Chap. 5).

The complete circuit from man to machine and back to man is the *control loop*. Information courses around this loop, which may be augmented by computers here and there. The successful operation of the teleoperator depends upon the successful encoding, transmission, and translation of this data stream.

Perhaps this portrait of the teleoperator control subsystem seems overly formal for the simple mechanical master-slave manipulator where the operator sees his task through a window (direct visual feedback), but it is none too rigorous and precise for the sophisticated teleoperators of the future which must work on distant planets, on the deep sea floor, and in other hazardous environments that man cannot penetrate safely.

MAN AS AN ELEMENT IN THE CONTROL SUBSYSTEM

The human operator eludes precise definition. If he did not, control engineers could formulate an elegant *human transfer function* or *human describing function* that would mathematically describe what man would do when confronted with feedback data and decisions to make. The human transfer function describes what a normal man will do given a specific input. In the next chapter, we will describe some of the human transfer functions that have been synthesized for extremely limited situations. Unfortunately, they have scant utility in teleoperator control theory, except for helping predict system stability and in very special situations. In teleoperators as nowhere else, man is an adaptable, rather unpredictable element that cannot be encompassed by formulas.

In lieu of precise mathematical human describing functions, words must suffice. It is common to describe man in terms of his *input-output* characteristics, just as if he were an electronic control component or *black* *box.*[4] The words, however, can only guide us in the design of the teleoperator control subsystem.

The sensory input channels leading to man's brain are many. We know how to use them but not how or why they work as they do. From this wide selection, only four of our senses are in actual use today in teleoperator work; vision, audition, and the cutaneous and kinesthetic senses; i.e., sight, sound, touch, and the sense of position and motion (Table 2).

Table 2 Some Input Channels of Lesser Importance to Teleoperator Design*

Sense	Sense Organ (s)
Rotation	Semicircular canals
Falling, rectilinear motion	Muscles, semicircular canals, otoliths
Taste	Tongue, mouth
Smell	Nose
Vibration, pressure	Skin, underlying tissue
Temperature	Skin, underlying tissue
Attitude, balance	Semicircular canals, otoliths
Bodily motion, position	Joints, tendons
Passage of time	?

*See tables 5, 6, and 7, Chap. 4, for a detailed description of the characteristics of man's senses of vision, audition, etc.

Sight is by far the broadest channel carrying feedback information to the operator. In fact, it is the *only* input channel in most teleoperator systems. This is true because sight is practically indispensable* in manipulatory tasks—we *have* to have it—and visual channels are relatively easy to build (windows, TV, etc.). Force feedback is present in mechanical and electrical master-slaves as well as some walking machines and man amplifiers currently under development. Proprioceptive feedback or sense of limb position can be achieved by using exoskeletal controls that maintain the same configuration as the actuators. The man amplifier in Fig. 3 possesses such exoskeletal controls. Touch sensation, as opposed to gross force feedback, is highly desirable in a teleoperator but sometimes not worth the cost of instrumentation; it has not been developed to the point where it is used regularly. Sound waves coming from manipulatory processes carry alarm or warning signals (viz., a dropped object); and for this reason a few manipulators incorporate microphones.

Despite the paucity of feedback channels in contemporary teleoperators, designers always have as their ultimate goal the faithful reproduction

*Manipulation by force feedback alone is possible but it is generally not efficient.

(occasionally, amplification) of most of the sensations that would normally be experienced by an unaided human actually doing the job of the teleoperator. In practice, they settle for much less. Of course, no one reproduces all aspects of a hazardous environment for the operator—just those aspects of the environment that will aid manipulation. For example, the forces experienced by the machine body of a man amplifier would crush the human operator if they were not attenuated.

Humans also have subtle input problems. For example, the all-important visual channel is subject to a great variety of optical illusions and signal distortion. Then, there is operator fatigue which can seriously distort the information presented to the decision-making and command-generating portion of the brain. Fatigue also lengthens the operator's reaction time. Finally, man's senses are far from the easy-to-analyze linear transducers that engineers like so much; that is, the intensity of a stimulus perceived by the operator is not proportional to the actual physical magnitude of the stimulus. Instead, each sensory channel seems to exhibit a different power law relationship.*

To illustrate the complexity of the problem, some evidence suggests that, if a system has anthropomorphic features, the operator instinctively employs his long-used anthropomorphic responses. This may be undesirable if the task or feedback is nonanthropomorphic. Yet, in hot-cell work the roughly anthropomorphic master-slaves have proven to be highly effective.

Human weaknesses are counterbalanced by unexpected strengths that transcend the usual adaptive and integrative powers. Airplane pilots, astronauts, and other operators of complex machines show a surprising ability to handle nonanthropomorphic displays and manipulate controls that certainly seem "unnatural." In fact, man *may* overpamper himself and unnecessarily restrict the machine by making his teleoperators too much after the human mold; although some engineers object to this contention.

The gist of this discussion of input channels is that the human operator may confound control theoreticians with his nonlinearities and unpredictability but that he also possesses useful properties that no artificial brain can yet match.

Once the human operator has digested the stream of input information and decided upon a course of action, he "emits" a train of command or output signals. Precisely what transpires between input and output in the human transducer has been argued by speculative philosophers for centuries. In other words, we really have little idea of how information is processed in the brain; and for practical purposes we do not really need to know.

*There is, however, a simple and fairly well substantiated law (Weber's Law) that states that for each sensory channel the ratio between the just noticeable difference in the perceived stimulus and the actual physical magnitude of the stimulus remains constant. More sophisticated laws also exist.[4]

To translate his commands into machine language, the operator has at his disposal his hands, feet, head, in fact any part of his body that moves, even his eyeballs (Chap. 6). By far the most useful output channel depends upon the motion of the human hands. In current teleoperator design, the preponderance of hand-actuated controls is even more marked because manipulators are really machine analogs of man; and it seems eminently logical to control hands with hands. Similarly, in a biped walking machine it is natural to control legs with legs.

When the teleoperator must be steered or flown, or it possesses more degrees of freedom than the operator can handle with his hands and feet, the human voice may serve as an output channel. Even today, machines can be designed to recognize a small array of spoken commands, such as "turn left" or "stop."

Suppose a handicapped person has no hands or arms to control his artificial limbs. Muscle-bulge switches and shoe switches are sometimes employed. More often, limb remnants and shoulder muscles activate prostheses. A promising human output channel, still in the research and development stage, translates the weak electrical signals created within the body by muscle action into electrical commands a machine can understand. Muscle action potentials (MAPs) form the basis of electromyographic (EMG) control of artificial limbs as well as other types of teleoperators (Fig. 10).

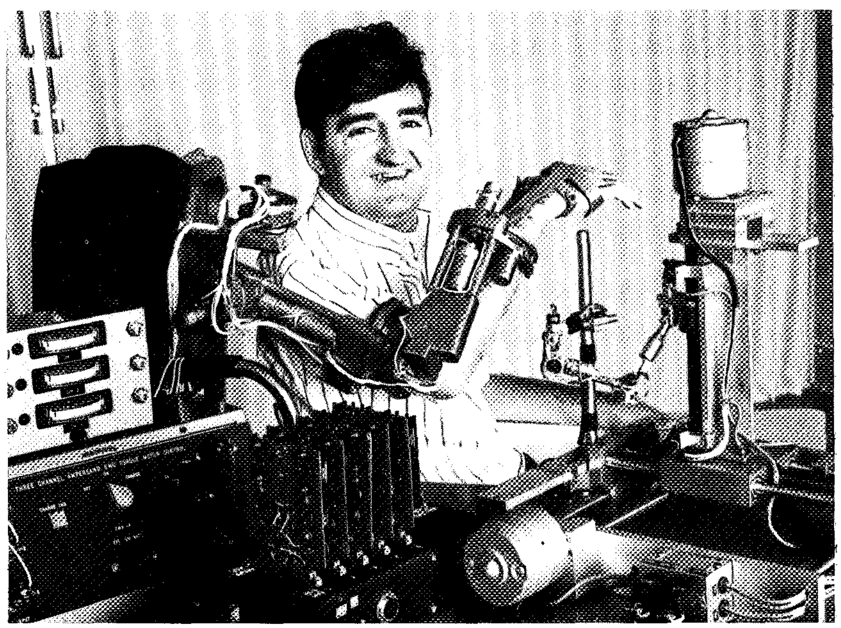


Figure 10 *An orthotic arm controlled by electromyographic (EMG) signals generated by the amputee's muscles. (Courtesy of Case Western Reserve.)*

SOME SPECIAL TELEOPERATOR CONTROL PROBLEMS

Most treatises on the human control of machines—*manual control*, as the dicipline is often called—deal with aircraft, terrestrial vehicles, and other machines with far fewer human characteristics than teleoperators. Because teleoperators simulate human traits, one would expect that matching the man and machine portions would be easy (Fig. 9). It is actually a most difficult task, one requiring for discussion a full chapter later (Chap. 4). Here, we merely list some of the more troublesome aspects of man-machine integration to illustrate how teleoperator control is different.

1. The operator is often located at a point far removed from the mechanical arms and hands he is controlling. In most terrestrial hot-cells, where good visual displays and force feedback exist, it is not too difficult for the operator to project himself into the working area; that is, identify his movements with those of the distant hands and arms. The problem here is the provision of good feedback in more difficult applications, such as undersea manipulation.

2. Great distances between the operator and the actuator subsystem introduce signal time delays that confuse the operator. This problem is serious in some space applications; viz., the round-trip signal transmission time to the Moon is about 2.6 sec.

3. A sophisticated teleoperator has so many degrees of freedom (over a dozen in many instances) that an operator is hard put to control them in concert unless both controls and actuators possess some anthropomorphic characteristics (Fig. 11).

4. If the motions and dimensions of the mechanical hands and arms do not correspond rather closely to the motions of the controls, operator confusion may result. For example, moving a control left should cause the appropriate actuator to move left. (See Table 3 for definitions of spatial and visual correspondence.)

As we shall see, man-machine integration difficulties such as these can be solved through the application of good *human engineering*, a subject that now includes the application of computer aids.

PERFORMANCE FACTORS

A cornerstone of systems analysis is the formulation of an overall figure of merit that describes the performance of weapons systems and other complex man-machine conglomerates in terms of a single parameter. The parameter "cost effectiveness" has achieved fame and some notoriety in many fields. Teleoperators have no such advantage; perhaps they are more subtle than weapons systems.

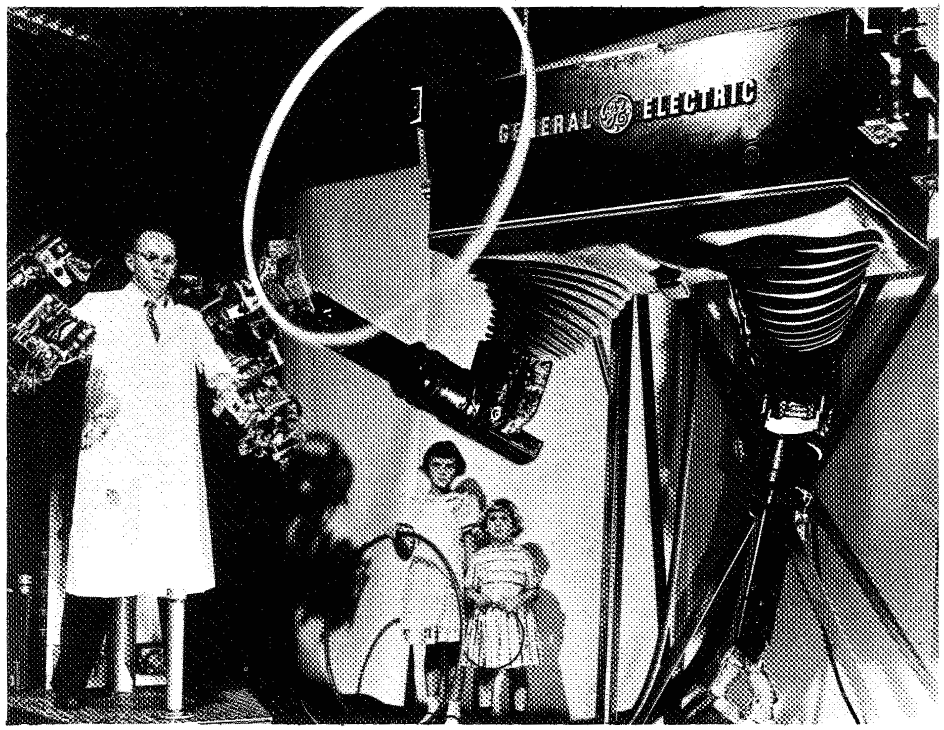


Figure 11 *This often-printed photograph of the General Electric electrohydraulic Handyman illustrates the degree of coordination possible between master and slave arms in a teleoperator with force feedback. The arm-paralleling controls exhibit anthropomorphic characteristics. (Courtesy of R. S. Mosher, General Electric Co.)*

Table 3 Some Definitions Used in Teleoperator Control

Open loop	No feedback of any kind to operator
Closed loop	Some kind of feedback is present. Psychologists call a loop "closed" when vision is present, but engineers usually reserve the term for nonvisual feedback.
Preprogrammed	Commands are prerecorded
Adaptive	Capable of making decisions based on past experience.
Robot	An adaptive machine that needs no human operator, usually humanoid in form.
Time delay	Command and feedback delay due to: (1) signal transmission line; (2) coding delay; (3) passive-process delay (inertial effects); and (4) human reaction delay.
Preview control	Use of predictive displays (with time extrapolation) to help overcome the effects of time delay
Supervisory control	Use of computers at the operator end to aid decision making and at the actuator end for adaptive control and application of subroutines.
Spatial correspondence	Actuators mimic motion of controls (used primarily to describe master-slaves and slaved TV systems).
Visual correspondence	Visual display slaved to position of operator's head
Degree of freedom	A dimension of motion in a teleoperator; viz., wrist rotation and elbow pivot.
Anthropomorphic	Actuators or controls resemble human body segments in terms of degrees of freedom and how they are articulated.
Quickening	The use of time derivatives of teleoperator motion to help the operator predict actuator position and compensate for time delay. (A distant cousin of preview control.)
Unilateral teleoperator	A teleoperator in which force and motion can be transmitted only from the operator controls to the actuators.
Bilateral teleoperator	A teleoperator in which force and motion can be transmitted from the operator controls to the actuators and vice versa; i.e., the slave arm can move the master arm. (Note: "bilateral" does not imply physical symmetry here as it does in biology.)
Rectilinear teleoperator	A teleoperator possessing several degrees of freedom in rectangular coordinates. Generally, these degrees of freedom are associated with over-head bridge-crane positioning systems. "Rectilinear" is often used incorrectly as a synonym for "unilateral." Joints with angular freedom are often termed "polar" in the literature.
Master-slave teleoperator	A teleoperator in which forces and torques are proportionally reproduced from the controls (master) to the actuators (slave). A master-slave is bilateral in at least seven degrees of freedom in each arm/hand. All degrees of freedom can be controlled naturally and simultaneously. This term was originated at Argonne National Laboratory.

In experiments with manipulators, notably at the U. S. Air Force's Aerospace Medical Research Laboratory, the time taken for a skilled operator to perform a manipulative task has been used as a gauge of merit. While useful in comparing different brands of manipulators, this parameter can hardly be expressed in terms of engineering design variables, such as number of degrees of freedom or speed of joint rotation. Teleoperator designers usually rely upon a group of secondary figures of merit, which are collectively optimized by experience rather than systems analysis. We now list those secondary figures of merit related to the control subsystem.

Figure of Merit	Definitions, Comments, and Intercomparisons
Torque, force, or grip	Applied to rotating joints and teleoperator hands. The control subsystem should be able to apply force and torque continuously or in graduated steps in response to the controls. Force multiplication between operator and actuator may be desired. Design levels depend upon task at hand.
Speed	The linear or angular rate at which a joint moves. Related to torque, force, and the mass of the mechanical hands, arms, and legs. Speed should be controllable in many applications.
Accuracy	An arm or hand is accurate if it responds to a command (say, rotate 30° clockwise) with some agreed-upon degree of precision. Precise motion requires good controls.
Ease of indexing	The ability of teleoperator appendages to move into prescribed configuration. Computer subroutines are sometimes used to index a teleoperator.
Articulateness	A measure of the number of joints and degrees of freedom. Each degree of freedom complicates the control subsystem.
Stiffness	A synonym for teleoperator rigidity. This is a desirable quality (see *sponginess*).
Friction	Energy dissipation during motion. This can tire the operator as well as degrade force feedback.
Inertia	A measure of the difficulty of accelerating and decelerating the actuators beyond the time lags caused by circuitry, mechanical linkages, and signal transit time. Inertia can cause overshooting and oscillations about a target position.
Sponginess	A characteristic of pneumatic teleoperators in which controls and actuators are connected

	by a compressible fluid. To some extent, good controls can eliminate sponginess (see *stiffness*).
Backlash	The amount a control must be moved in the reverse direction before the commanded joint responds.
Stability	The ability of a teleoperator to move smoothly from one configuration to another and maintain it without jitter, hunting, or divergent oscillations.
Sensitivity	A teleoperator is sensitive if a slight motion of the controls causes actuator motion. Often "play" or a "deadband" will be built into the control subsystem to prevent excessive sensitivity.
Cross coupling	This occurs when commanded motion in one degree of freedom creates motion in another. The control subsystem design should preclude cross coupling.
Drift	Drift occurs when electrically and hydraulically actuated teleoperators may move slightly in a continuous fashion due to servo "leakage."
Compliance	The match between the manipulatory requirement of a task and the motion capabilities of the teleoperator (Fig. 11). Good control design can improve the dynamic match.
Reliability	The probability that the system will operate at some stipulated level of performance for a stipulated length of time. The control subsystem must help the overall teleoperator system meet reliability goals.
Fail-safe capability	When a teleoperator fails or loses power, the control subsystem should assure that the actuators retain their configurations. (Collapse could be disastrous in a man-amplifier.)
Self-protectivity	Limits switches and other control devices should prevent a teleoperator from damaging itself.
Cost	Self-explanatory
Power requirement	Power is critical in space and undersea work. The control subsystem should draw as little power as possible.
Support-equipment requirements	The total of all auxiliary equipment; such as repair and maintenance facilities, fuel-supply facilities and vehicles; and, of course, the trained technicians associated with this equipment.
Operator skill required	The effective matching of the man-machine interface can reduce skill requirements.

Chapter 3

CONTROL THEORY

OPEN-LOOP CONTROL

Imagine driving an automobile with the windshield blacked out and with no "feel" in the steering wheel. Without visual and force feedback, catastrophe would soon result. Control under these conditions is termed "open-loop," and though it would seem a disastrous approach to teleoperator control it is employed in special circumstances.

One such circumstance occurs whenever the control of a teleoperator is relinquished by the human operator to a preprogrammed set of instructions—say, a preprogrammed subroutine in an on-board computer that automatically stows a manipulator on a submersible. Open-loop subroutines are essential in supervisory control; in fact, the use of computers to relieve the operator in routine situations and provide special nonanthropomorphic skills is so important that we devote the next section to this subject.

Meanwhile, teleoperators that are normally operated in a closed-loop mode may revert to open-loop control under the following conditions:

1. If feedback is temporarily cut off, based on cues acquired before the displays were blacked out, an operator can usually make several movements safely. The feedback-deprived automobile driver mentioned above can, for example, pull safely off the road if he knows where he was before the blackout and if the traffic is light.

2. If feedback information suddenly becomes unintelligible due to noise or becomes too complex for the operator to cope with, the operator might well proceed open-loop fashion to some safe holding position.

3. If there is significant time delay and the operator cannot discern the consequences of his actions for several seconds, he may adopt a move-and-wait strategy in which each short open-loop move is prefaced by an analysis of the consequences of his last move. The operation of the Surveyor lunar surface sampler employed this philosophy. (See later section in this chapter on time delay.)

4. If a tedious repetitive task is anticipated, one cycle of the operation can be carried out once under closed-loop conditions, with all control information being recorded, and thereafter accomplished by supervisory control without the operator in the loop.

PREPROGRAMMED CONTROL

In preprogrammed control, the operator turns control of the teleoperator over to a machine, one with a memory that contains instructions for carrying out a given order. The instructions may be stored in a computer's memory or engraved in analog form on a grooved rotating disk or cam, like the famous Jaquet-Droz automatons in the late 1700s. The operator may transfer control by simply pressing a button, typewriter keys, or by reading a deck of punched cards into a computer. Or, in principle, the machine portion of the teleoperator may intentionally bypass the operator in an emergency and switch in a preprogrammed subroutine. A common feature of preprogrammed control is the absence of any feedback to an operator that would permit any modification of the action—the "manipulator stow" subroutine, for example. Once the subroutine is in action, it is played out. In other cases, the human operator can inhibit action and correct errors.

It is often desirable to initiate a subroutine which requires internal feedback of some sort (unseen by the operator) to carry out an instruction. An operator may in fact cut himself out of the loop and switch in a variety of supervisory subroutines, including: (1) the type of open-loop preprogrammed subroutine just described; (2) an automatically controlled closed-loop subroutine that utilizes feedback signals to reduce the task error, for example, the automatic movement of the teleoperator arms into configuration A; or (3) an adaptive or artificially intelligent subroutine that makes its own decisions on how to best carry out an operator's directive, perhaps by transferring object X to point B around an obstacle. Closed-loop subroutines (2) and (3) of course require feedback, whereas open-loop subroutine (1) moves ahead oblivious to feedback. In effect, we have established the matrix of operator-machine control relationships illustrated in Fig. 12.

Is there a formal theory of open-loop teleoperator control? There is little to report here. Naturally, a strategy is important in an open-loop move-and-wait situation like that encountered in operating the Surveyor surface sampler (Fig. 13). If one wishes to dig a trench on the Moon, one does not at first take big bites from an unknown medium that might damage the sampler itself. Instead, one devises a strategy composed of moves such as: Extending a sampler arm in increments of a half-inch at a time, waiting between moves to see the results.* In other words, adopt a "move gingerly" strategy.

Beginning with Ernst's work in 1961[5] several researchers, notably at M.I.T. and Case Western Reserve, have interposed a digital computer between the human operator and the manipulator.[6,7] The software and hardware employed in these NASA-supported experiments will be described in Chapter 5. A typical open-loop computer instruction during a stow subroutine or reactor core disassembly might be: Move joint C 5° clockwise. The

*Preprogrammed tapes controlled some Surveyor sampler arm motions.

TYPE OF CONTROL

	OPEN-LOOP	CLOSED-LOOP
OPERATOR IN LOOP	MOVE-AND-WAIT STRATEGY	NORMAL TELEOPERATOR OPERATION
OPERATOR OUT OF LOOP	PREPROGRAMMED, SUPERVISORY CONTROL	ADAPTIVE CONTROL; ARTIFICIAL INTELLIGENCE; AUTOMATIC CONTROL; SUPERVISORY CONTROL

Figure 12 *Matrix of various teleoperator control situations. To qualify as a teleoperator, the machine should operate with the operator out of the loop only in special situations where the human operator cannot cope with the task or where he wishes to relieve the task burden.*

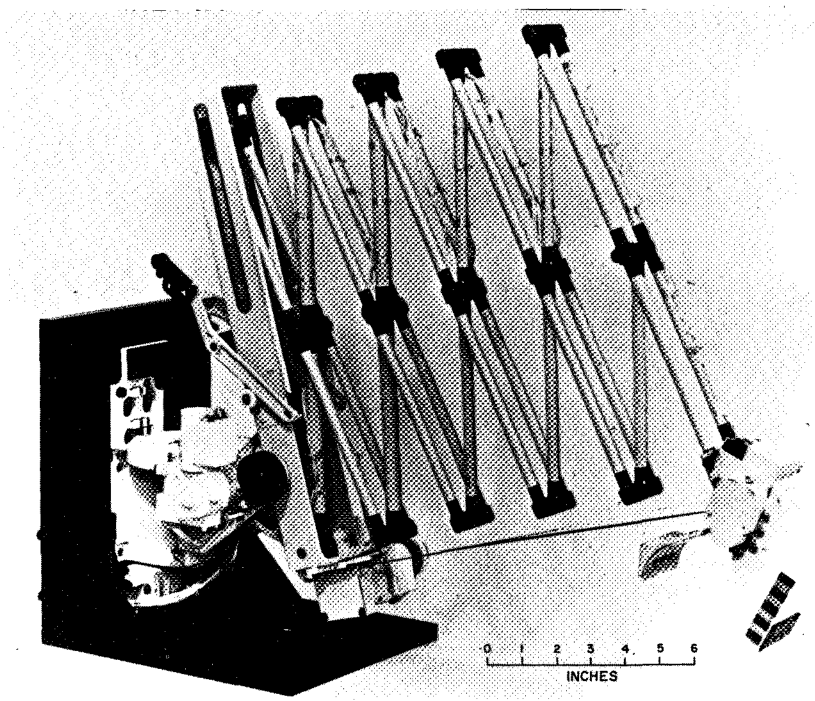


Figure 13 *The Surveyor surface sampler. (Courtesy of D. Le Croissette, Jet Propulsion Laboratory.)*

computer merely acts as a switch in this case, turning on the motor driving joint C for the requisite number of revolutions. In open-loop control there is no feedback to assure the computer that joint C really rotated 5°, although a limit switch would probably be installed to indicate completion of the task.

CLOSED-LOOP CONTROL

Sophisticated control systems depend upon feedback; teleoperator controls are no exception. Teleoperators are normally operated with man in the loop and with visual feedback. Even many of the supervisory subroutines that relieve man of participation in control depend upon internal feedback signals to carry out their instructions (Fig. 12).

A large body of theory has grown up around the concept of feedback control.[8,9] Our objective here is to summarize some of the conventions and the general teleoperator approach.

The essence of feedback control is, of course, feeding some of the output back into the input to modify it. One tries to reduce the error with feedback, but sometimes this tactic is not successful and instability occurs. Some important control conventions are illustrated in Figs. 14 through 16. The first of the "block diagrams," Fig. 14, illustrates how an input, R, is affected by a

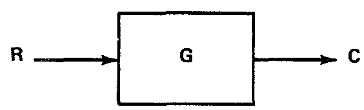


Figure 14 *A simple open-loop control situation.*

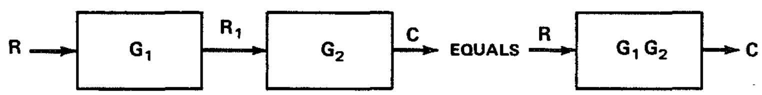


Figure 15 *Two control components in series.*

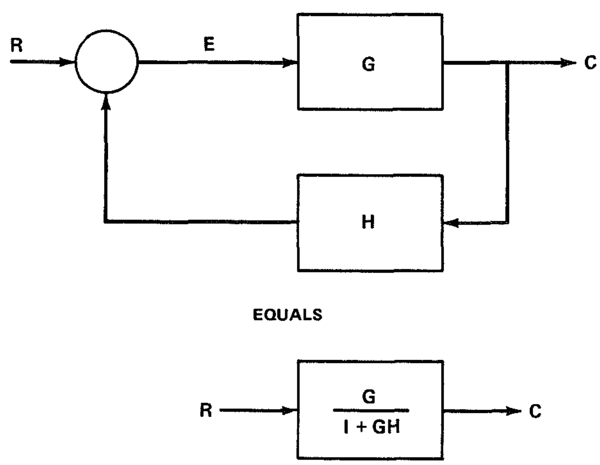


Figure 16 *A fundamental equality in control circuit theory.*

control system element symbolized by the block and is algebraically represented by the transfer function, G. The G symbolizes "something done" to the input signal. The output, C, is given by $C = GR$. The block diagram of Fig. 14 is completely equivalent to the equation $C = GR$. The control element thus represented is obviously linear. If two control elements are in series (Fig. 15), the overall equation is $C = G_1 G_2 R$. The Gs are often called forward transfer functions and may include the human transfer function.

When feedback exists, control theory convention calls for the addition of the subtractor symbol, the circle in Fig. 16. Here, the input R and the feedback signal, HC, are subtracted: $E = R - HC$; where H is the feedback transfer function and E is the actuating signal. Because $C = EG$, we can also write:

$$C = \left[\frac{G}{1 + GH}\right] R$$

This equation and Fig. 16 represent closed-loop control with negative (degenerative) feedback. Feedback can be positive as well as negative. Also, its frequency, phase, and other characteristics can be modified to achieve the goals of the control system designer. (For a grounding in control system theory, see References 8 and 9.)

For all the simplicity of Fig. 16 and the equivalent equation, they are really a facade for more complex equations describing the dynamics of the control system as measured in terms of its input and output voltages, displacements, or whatever the physical parameters may be. To transform the usually complex equation expressed in physical parameters into the G, H, R, C, E representation, one utilizes the well-known Laplace transform. Again, the reader should consult the many textbooks on control theory.

Conventional feedback control theory is applicable in principle to teleoperators with man in loop and when the teleoperator is controlled by automatic control subroutines that depend upon feedback, almost all extant teleoperators fall into these two categories. We specify "conventional" control theory because later in this chapter we will describe some new theoretical developments oriented specifically toward teleoperators.

ADAPTIVE CONTROL AND ARTIFICIAL INTELLIGENCE

The word "adaptive" is employed fairly loosely in the control literature. Generally, an adaptive control system is one which adjusts to meet changing circumstances. In this sense, any feedback control system is really adaptive. In this book, however, we narrow the meaning to include only control systems that can cope with changing external circumstances beyond the capacity of simple feedback control. Two examples: avoiding an obstacle and finding the quickest way to take a manipulator from configuration state A to state B. In other words, judgment and decision-making are involved in adaptive control; something beyond the ken of a "deterministic" feedback control system such as a thermostatic temperature regulator. The distinction, however, is rather fuzzy.

Even fuzzier is the distinction between adaptive control and artificial intelligence. An artificially intelligent machine would not only be adaptive but would also have the ability to learn from past mistakes and be able to devise strategies of a general nature to reach goals set by itself—or perhaps goals set by man if the machine still depends on him at this stage of development.

A teleoperator, being a man-machine system, is always adaptive and intelligent when man is in the loop because man has defined these characteristics from his analysis of himself. But when operating in a subroutine, we often look to the machine portion of the teleoperator to do a little thinking for itself.

Before confining the discussion to machines exclusively, we would like to mention an interesting body of theory developing around the adaptive behavior of the human controller.[10-12] The approach is much like that used in "tracking experiments", wherein an operator tries manually to follow a target or reduce an error signal.* In adaptive tracking experiments, however, instead of merely shifting the target with time, the entire dynamic system may be altered and the operator has to revise his strategy in midcourse based upon his observation of the altered system. Eventually, this approach may prove useful in teleoperator control because we obviously wish to describe accurately how the human half of the teleoperator adapts to changing ground rules.

To illustrate how feedback theory also applies to subroutines, we describe how the computer-controlled manipulator at Case Western Reserve assures that it has correctly carried out an instruction.[7] If the subroutine requires that the manipulator move to a specified configuration (or "state"), the computer compares the current configuration of the manipulator, axis by axis, with the desired configuration. The differences in axis positions are converted into analog voltages. These voltages—really error signals—drive the axis motors until the errors disappear. The resultant configuration should be the desired one since all errors have been nulled. The feedback in this example consists of the voltages (from axis potentiometers) representing the manipulator configuration as a function of time. It is classic feedback control. The operator, though, is not in the loop during this operation.

The Case computer-controlled manipulator also exhibits a kind of adaptive behavior in its ability to avoid obstacles in its path. If the computer

*The so-called "tracking experiments" are the foundation of manual control theory. In these, a subject tries to follow a target or reduce an error. See later discussion under Manual Control and Tracking Theory.

memory knows the location and configuration of the obstacle situated between the initial and final manipulator configuration, it will first check to see if other terminal arm-hand configurations can place the hand in the right position. If so, the obstacle may be avoided by proceeding to one of these directly. The computer checks to see. If obstacle avoidance is still impossible, the computer will explore several paths leading around the obstacle, select the one requiring the least transit time, and set the manipulator in motion along this path (Fig. 17). Clearly, a judgment and a decision have been made.

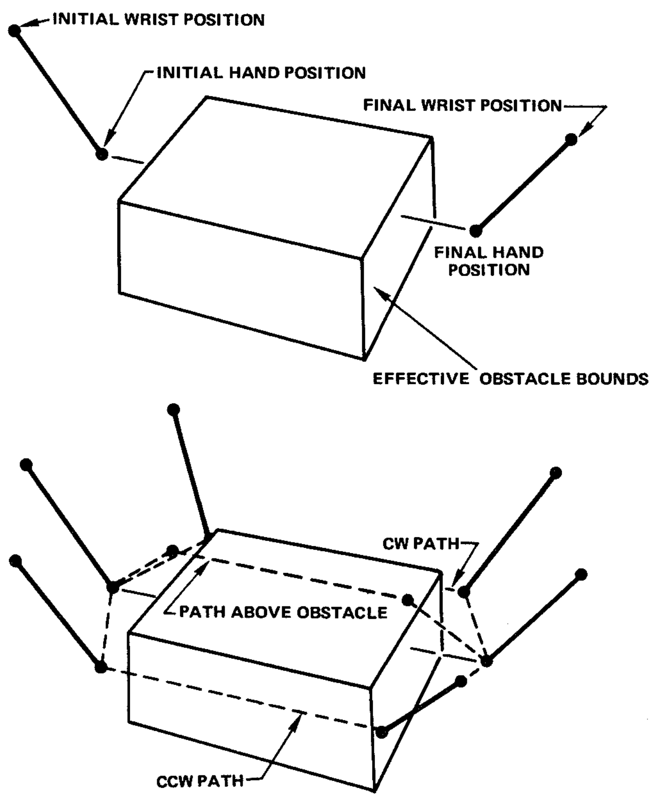


Figure 17 *Some possible obstacle evasion paths tested in the Case Western Reserve computer-controlled manipulator experiments.* [7]

Similar obstacle-avoidance studies are being pursued under NASA contract by Sheridan's group at M.I.T. using sets of heuristics arranged according to a priority criterion.[13] One heuristic approach might be to try a series of straight line motions tangent to the obstacle's peripheries.

Most of the walking machines we see today are preprogrammed and open-loop. They tread away blindly, regardless of the terrain. R. J. Hoch and his associates at Battelle-Northwest Laboratories have conceived of a method that may make walking machines adaptable to varying terrain.[14] The germ of the Battelle idea lies in the short-term memory of a small computer and the quantizing of the control system. Control of the walking machine by pistons is accomplished by a series of discrete pulses, N pulses per second to each piston. Initially, the control pulses would be those that would carry the vehicle over ideal, non-varying terrain at the gait and speed set by the operator. In this mode, the operation would be preprogrammed; but as the terrain departs from ideality, the piston backpressures (the discrete feedback pulses) would also depart from those expected from an ideal terrain. The differences between the ideal and the real signals would be stored in the control computer memory and used to modify subsequent control pulses. The older the differences the less their weights in determining the next cycle of control pulses. The Battelle scheme would also employ sensors that feed back data on vehicle stability that may bypass the normal controls in favor of some emergency subroutine—say, one that prevents the vehicle from overturning. The use of past deviations from ideality in determining future action is a form of learning. We humans are adaptive walking machines, except that we can usually see the terrain ahead and add this knowledge to that from past experience. Note that the Battelle walking machine would not have the human operator in the loop while controlled by the computer; it would operate under supervisory control during these periods.

A different approach to adaptive control has been proposed for artificial arms by Lyman's group at the University of California at Los Angeles.[15] Here, the strategy is to increase or decrease the control system gain as the average operator error decreases or increases, respectively. The error is measured in terms of overshoot and undershoot of a target. In this case, the machine adapts itself to the operator's skill. The operator "trains" the machine here, whereas the Battelle walking machine was trained by the task itself.

Since the attainment of intelligence by a machine is a matter of debatable definition, many will say that an adaptive walking machine is definitely not intelligent. Yet, the Battelle approach permits the redirection of action based on learned facts. In the usual case, a teleoperator would not be an artificially intelligent robot because man is in the loop adding his brain. One can conceive of situations, though, wherein man divorces himself more and more from detailed control, giving more and more executive orders, such as "pick up object A and move it to point B." Considerable work of this type is underway. At M.I.T.'s Project MAC, Minsky is building an autonomous robot;[16] so is Rosen at Stanford Research Institute.[17] One can consult Feigenbaum and Feldman[18] for discussions of specific machines like the General Problem Solver and the Logic Theory Machine. Almost all of today's teleoperators require the full real-time involvement of man; computer control of teleoperators with nearly autonomous machine partners has been demonstrated but is still far in the future.

STABILITY

Stability exists in a control system when the transients created by a disturbance eventually die out. If the transients do not completely die out, but remain bounded, *limited* stability exists. Instability plagues only closed-loop control systems, because only when the system output can reinforce the input can divergent behavior occur. Most texts on control system design devote considerable space to stability criteria and the Nyquist diagrams that predict the stability of a control system.[8] The reader should consult these texts for details.

Teleoperators, being mainly closed-loop systems that incorporate man, naturally face stability problems. The intimacy of the man-machine interface poses a special problem in teleoperator design. A human operator may make mistakes, get tired, become confused, and otherwise contribute to instability. The time delay of feedback data is a case in point because too great a time lag disconcerts the operator and may stimulate divergent transients.

THE TIME DELAY PROBLEM

Many people have experienced the disconcerting effects of delayed audio feedback, particularly in public address systems. Delayed visual and force feedback can compromise teleoperator control in a similar fashion. In this chapter, we define the problem and look at some "preview control" models; Chapter 6 covers the predictor displays that have been designed to help solve the time delay problem.

NASA has been concerned with transmission delays resulting from the finite speed of radio signals over the great distances in outer space. Between Earth and Moon, the round-trip signal time is roughly 2.6 seconds—enough to disconcert an Earth-based operator of a lunar machine (Fig. 18).

Besides the signal propagation time delay, feedback information also encounters electrical circuit and mechanical device delays. The operator in the control loop also slows signals down. Wargo has summarized human delays for one-choice situations as follows:[19]

Receptor delays	1–38 milliseconds
Afferent transmission delays	2–100
Central process delays	70–100
Efferent transmission delays	10–20
Muscle latency and activation delays	30–70
Total delay	113–328 milliseconds

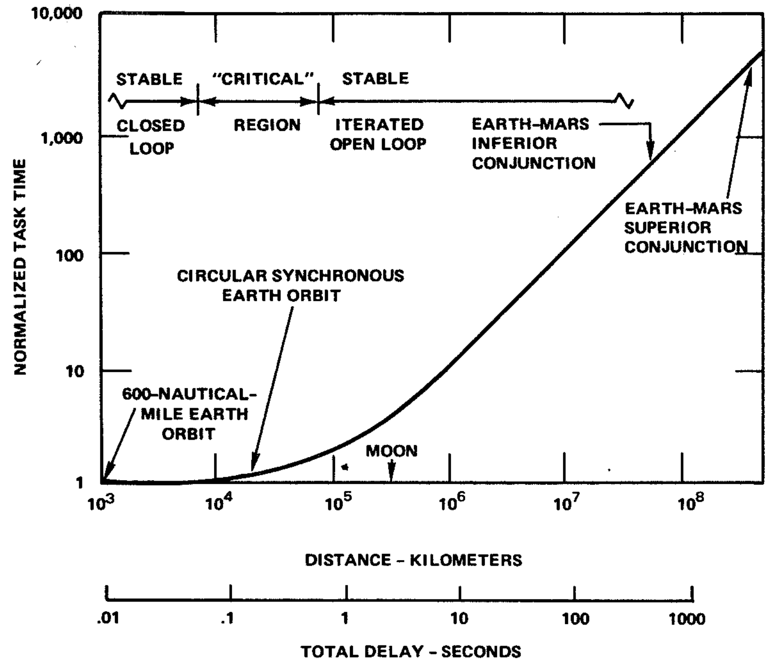


Figure 18 *Normalized task time vs. total time delay. A critical region, around 0.25 sec, where operator confusion is possible, occurs in space missions at very high orbits. Move-and-wait operator strategy would be a successful but slow strategy for work on the Moon and planets.*

These figures are for alert, pre-warned subjects. Reaction times lengthen when the unexpected occurs and when the choice is a complicated one. Human delays and equipment delays are usually much smaller than those NASA anticipates from propagation delays in space exploration.

The portion of the overall time delay that disconcerts the operator is that part that prevents him from seeing the immediate consequences of his actions. Ferrell and others have summarized past work in the field of delayed sensory feedback.[20,21,22] The early studies involved tracking experiments of various kinds with delayed visual feedback. All of the studies concurred that time delay was deleterious to performance. In connection with its projected remotely controlled lunar vehicles, NASA has sponsored work at Stanford University[23] which indicated that driving performance worsened with increasing time delay. The situation deteriorated faster as vehicle speed increased, as the vehicle course became more complex, and as the television field of view narrowed. Similar effects have been noted for delays in auditory feedback. Recent theoretical work by W. H. Thompson at ANL indicates that force feedback, too, is of diminishing utility as time delay increases (see Bibliography).

Some pioneering work with the effects of time delay on whole-arm motions (many degrees of freedom) have been carried out by Karl U. Smith, at the University of Wisconsin. Time delay can apparently be understood in terms of feedback theory and the perturbation of the operator's internal synchronization.

Also applicable to teleoperator control were Ferrell's 1963–1964 experiments with a two-dimensional manipulator with variable time delay in the visual feedback.[20] The manipulator operators in this case were able to pace their activities and work out strategies that suited them best. The tracking and vehicular experiments, in contrast, force the operator to synchronize his activities with the input signal.* Ferrell found that task completion time increased with both time delay and task difficulty (Fig. 19).

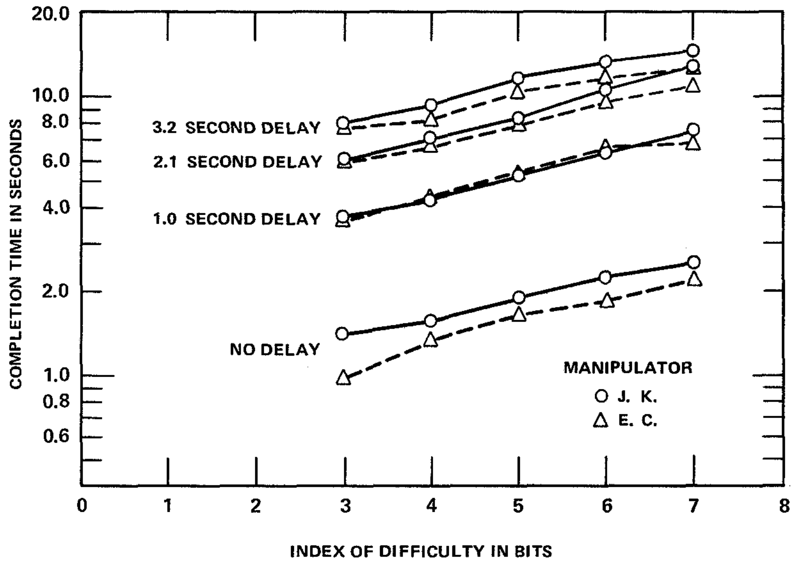


Figure 19 *Task completion times as a function of task difficulty from Ferrell's experiments.*[20]

Some important conclusions from Ferrell's work were:

1. Both operators independently adapted a move-and-wait strategy as the best and least confusing solution to the unnatural time-delay situation.

2. There were no unstable or oscillatory movements. This fact was attributed to the adoption of the open-loop move-and-wait strategy.

*This is one reason why tracking experiments in the manual control field have limited application to teleoperator control; an application where the operator moves at his own speed.

3. The operators found the work tiring and difficult, but not emotionally upsetting as other operators have reported for forced-pace time-delay tracking experiments. Trials where these operators were asked to use a move-slowly strategy did, however, disconcert them.

In summing up, time delay (and task difficulty) can be overcome by taking additional time—mostly waiting time between successive operator moves and the returned feedback.

While it is not yet apparent just how tracking theory and experiment apply to teleoperator control, numerous tracking experiments involving time delay have been carried out and some "modified" human transfer functions have been generated.[24,25] Note that there has been no attempt to evolve a mathematical model for *manipulatory* task performance involving time delay.

Suppose that the extra time required by the move-and-wait strategy is unacceptable; what can be done? In Chapter 6, we will describe some predictor displays that aid the operator working under a time-delay handicap by giving him feedback extrapolated into the future on the basis of known physical laws. In the present chapter on theory, we look at the so-called "preview models," which are really surmises on how an operator extrapolates his machine, the environment, and himself into the future.

The basic ideas behind preview models were published by Ziebolz and Paynter in 1953.[26] Kelley adopted these ideas in his Predictor Instrument in 1960.[27] Particularly pertinent to the teleoperator field are the preview models of Sheridan which incorporate prediction and planning aspects.[28] Sheridan's three models may be termed: (1) the "extended convolution" preview model; (2) the "dynamic programming," optimal trajectory, preview model; and (3) the Ziebolz controller preview model. The Ziebolz controller, which is a key ingredient in many preview models, is essentially a fast-time predictive model (or analog) of the system under control. To date, preview models have been developed around tracking experiments, where theorists have some confidence that they have valid mathematical representation of the control process. As mentioned before, the application of these models to teleoperator tasks is questionable.

One might summarize the time-delay situation by noting that: (1) the problem must be solved if teleoperators are to be effective over long distances; (2) current theory has so far offered little help; but (3) operators facing the problem solve it naturally by moving and waiting.

MANUAL CONTROL AND TRACKING THEORY

Earlier in this chapter, we have occasionally mentioned tracking theory—perhaps a little too disparagingly. Nevertheless, modern manual control theory is largely built upon a foundation of tracking experiments. These quantitative experiments form the only real basis for evolving and testing hypotheses in manual control. And manual control theory is the only kind of control theory we have that includes in the loop the human operator with all his idiosyncracies.

Three main types of tracking are recognized:

1. Pursuit tracking, wherein the operator sees both the moving target and his own corrective responses (Fig. 20). A common analogy is a duck hunter using a gun with an open sight. In laboratory practice, the operator tries to follow a moving target, say, a moving spot, using a joystick or some other control.

2. Compensatory tracking, in which the operator sees only the *differences* between the moving target and his response; i.e., the error (Fig. 21). In this type of tracking, the operator attempts to null the difference signal.

3. Precognitive tracking, which exists when the operator has complete information about the target's future—as in shooting at a duck in a shooting gallery. In the true sense of the word, this is not really tracking.

Which of these kinds of tracking have application to teleoperator control? Pursuit tracking applies if the teleoperator is trying to pick up or perhaps hit a moving object, a very rare situation in present-day teleoperator practice. In manipulation, the targets are generally stationary; so is the environment. In picking up an object, the operator first directs the manipulator hand to the general area of the target in a gross movement; then, in a series of fine adjustments, the hand is accurately positioned and the jaws closed. The same kind of coarse-fine "tracking" occurs when the target is moved from position A to position B. But which of the three main varieties of tracking describe the situation best? Obviously, precognitive tracking is closest, but it is not bona fide tracking at all. No formal theory exists for precognitive tracking.

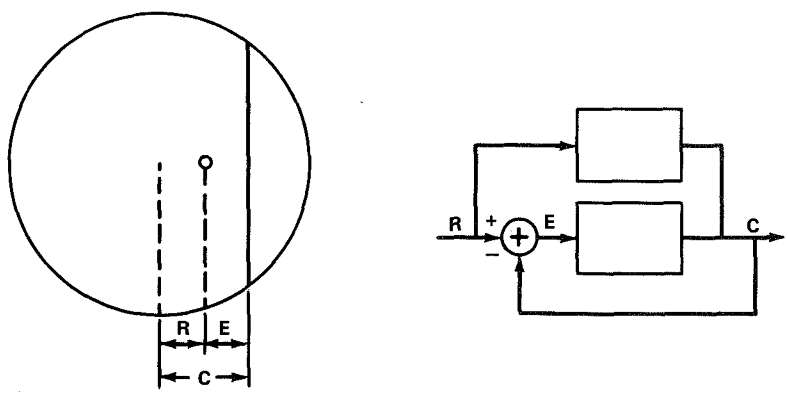


Figure 20 *In pursuit tracking, the subject tries to align the solid vertical trace with the target circle.*

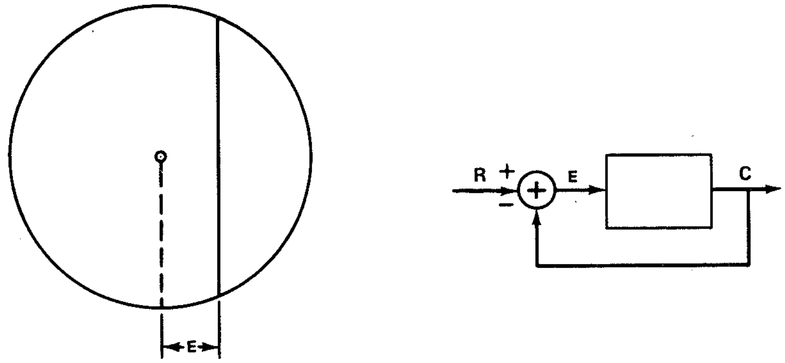


Figure 21 *In compensatory tracking, the subject tries to null the error, E.*

There are, however, elements of pursuit tracking that may be applicable. For example, the first gross movement of the manipulator hand to the region of the target is akin to getting the duck in the gun sights, and the fine motions prior to grasping the target really involve nulling out the position errors the operator sees visually. In sum, there is no single type of tracking that seems to cover teleoperator action. Further, there is no theory at all that really grasps the planning and strategic thinking of the person controlling a teleoperator.

These things being so, why bother to discuss tracking theory at all? The answer must be that tracking theory gives us the only quantitative insight into the behavior of humans in control loops, despite its acknowledged drawbacks. Any comprehensive theory of teleoperator control (including the operator) must build on (or alongside) manual control theory.

THE HUMAN TRANSFER FUNCTION

Tracking theory got its start in England and America during World War II in connection with gun pointing or "fire control." Elkind has reviewed the development of tracking models[29] and notes that despite some twenty years of research the "...relative lack of progress is not so much a result of lack of interest and effort as it is a consequence of the complexity of the human as a controller and of the interaction between him and the rest of the control system." During World War II, Tustin introduced the idea of representing the dynamic response of a human operator by a linear transfer function.[30] Since the War, most effort has gone into a search for a human transfer function in tracking tasks. To review this early work, the reader should consult such review articles as those by McRuer and Krendel[31] and Sheridan.[32]

The aim of manual control theory—or teleoperator control theory for that matter—is the description of the human operator in terms of a human transfer function that will put him on a par with other predictable control circuit elements.

In attempting to describe the human as a servo element, a tracking experiment is set up that places the subject in a control loop, provides a variable input or stimulus, and measures the human response. Classically, this is done with a continuous input signal that varies over a wide frequency range or bandwidth. The experimental response in terms of bandwidth, phase change, and so on, leads to the human transfer function. The literature in this field is so voluminous (see References 33 to 36 for review articles) that we can only touch on a few high points.

The hope of most theoreticians and experimentalists is for linearity. Tustin's early work in the late 1940s (and later studies) discovered a linear term in the human transfer function approximated by:

$$H(s) = Ke^{-\tau s}(1 + T_L s)$$

where $H(s)$ = the human transfer function as a function of the Laplace variable, s

K = the gain coefficient, equal to about 22

τ = a time delay term, equal to about 0.3 second for Tustin's work

T_L = a lead term, equal to about 2.3

Tustin also found a remanent term which was not linearly related to the input. The schematic representation of this situation is shown in Fig. 22. The

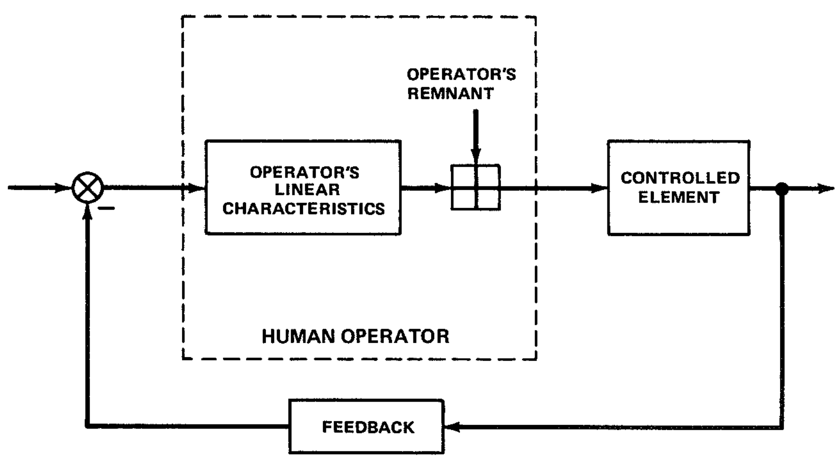


Figure 22 *Diagram of the widely accepted quasilinear model of the control circuit containing a human operator.*

situation was further complicated by higher frequencies in the output than had been in the input, obviously these were operator-induced. Delay times were often much greater than 0.3 second. Furthermore, output was often disproportionate to the input, sometimes even of different sign!

Many other studies followed Tustin's.[31,37] A simple, generally accepted form of the linear portion of the transfer function is now taken to be:*

$$H(s) = \frac{Ke^{-\tau s}(1 + T_L s)}{(1 + T_N s)(1 + T_I s)}$$

where T_N = a neuromuscular lag time constant
T_I = a compensatory lag time constant

When expressed in terms of output (θ_0) and input (θ_i) rather than the Laplace transform, the relationship is:

$$\theta_0(t) + (T_N + T_I)\frac{d\theta_0(t)}{dt} + T_N T_I \frac{d^2\theta_0(t)}{dt^2} = K\left[\theta_i(t - \tau) + T_L \frac{d\theta_i(t - \tau)}{dt}\right]$$

In modern compensatory tracking experiments τ averages about 0.15 ± 0.03 second. A good operator tracks poorly when the input exceeds one cycle per second (see Fig. 23). For discussions of experimentally determined values of the other parameters, see Kelley's book.[27]

One question that inevitably arises is whether the human transfer function applies to situations involving more than one loop or degree of freedom. This is certainly the case in any practical teleoperator. Several studies have been performed for multiloop situations.[38,39] These generally show the classical human transfer function is not as well confirmed as it is in single-loop situations.

The models of the human operator discussed above are usually characterized as "time-invariant and quasilinear." In other words, the operator is assumed to be a static, nearly linear circuit component; and of course he is neither. Sheridan,[40] McRuer[37] and others have tried to take into account the tendency of the operator to change his transfer function as the situation demands. Man "adapts." He also gets tired with time. Obviously, the human operator is far from time-invariant. So far, these efforts have not produced any widely useful time-dependent models.

Most tracking experiments employ visual feedback. Teleoperators, however, frequently supply the operator with force feedback. What little is known about the human transfer function in the presence of force or audio feedback indicates that the general mathematical form obtained in visual experiments remains satisfactory.

*There are many other models—some considerably more complex.

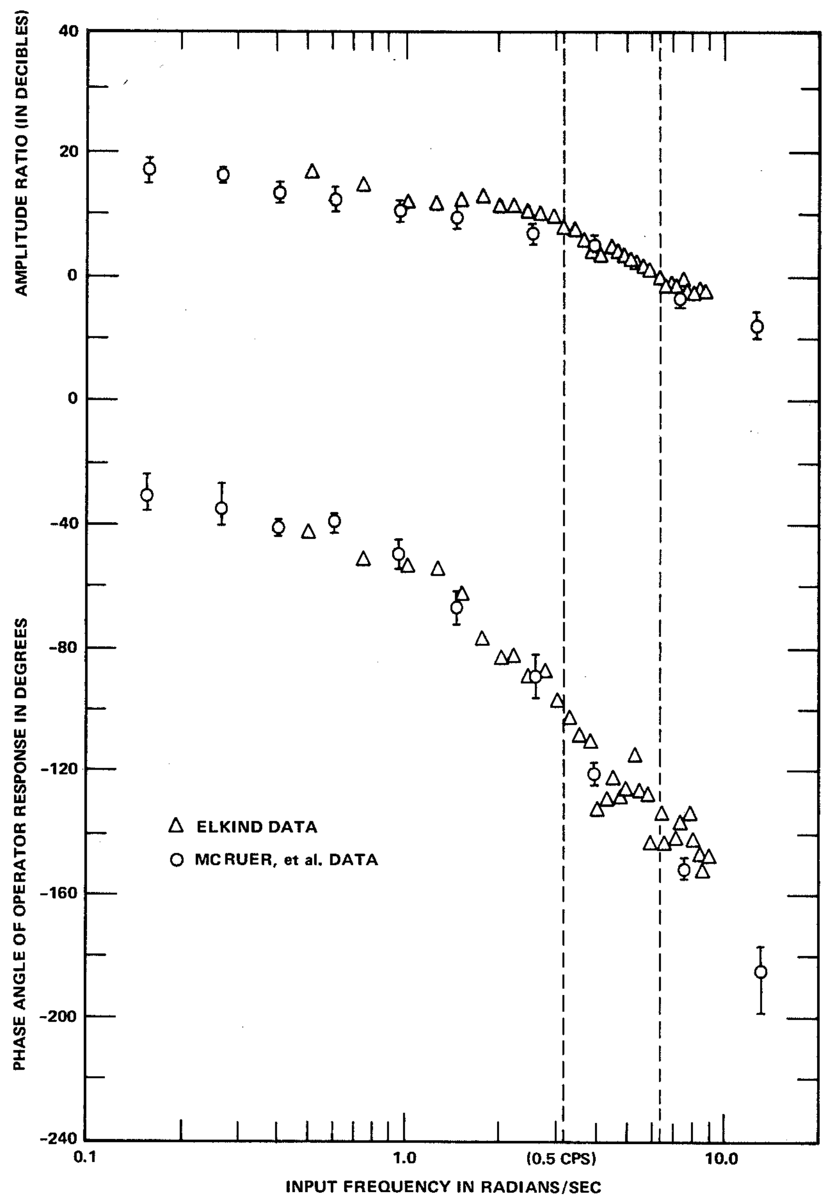


Figure 23 *Amplitude ratio and phase angle vs. input signal frequency of a typical human operator describing function.*[37]

Early studies tacitly assumed that the human controller is a continuous circuit element. Evidence exists, however, that human perception, perhaps cognition and other human functions, are discontinuous. These observations have led to the so-called "sampled-data" model of the human controller.[41,42] The applicability and utility of the sampled-data approach are controversial subjects at present. Some experiments do not support the model, some do. Fogel's recent NASA-sponsored work should be consulted for the "pro" side of the argument.[42]

The critical question after all this exposition is whether the models of the human controller can help us design better teleoperators. The human transfer function approach has only very limited applicability to manipulation, regardless of its demonstrated success in describing single-loop tracking experiments. In reality, it does not try to describe manipulation at all. The tracking experiments that determine the human transfer function and the constants in its mathematical representation do give us some insight into the servomechanism properties of the human operator. Human reaction time and bandwidth, for example, come out of tracking studies, although they depend upon the situation and must be used with caution. At best they can be considered "calibration functions." Regardless of the drawbacks of human modeling (Table 4), a start has to be made somewhere.

Table 4—Comparisons Between Human Transfer Functions and a Real Human Operator*

Human Transfer Function	Human Operator
Input has same number of dimensions as output	Typically input has more dimensions than output
One display or feedback channel	Multiple feedback channels
Assumes impoverished display format	Sophisticated multidimensional displays
Does not include explicit representation of task or environment	Operation vitally affected by understanding of task and environment
Restricted to present error, fixed weightings of past, and derivatives	Response based on remembered past and predicted future
Cannot remember; can only summarize signals by integration	Can remember, modify response on basis of past experience
Cannot predict input or output; response is an arbitrary weighting of error, lead, and lag terms.	Can predict and adjust response to minimize future error.

*Adapted from Kelley.[27]

SOME APPROACHES TO TELEOPERATOR CONTROL THEORY

Granted the weaknesses and general inapplicability of classical manual control theory to teleoperators, what has been done in the way of formulating a useful description of teleoperator control processes? Not a great deal! This should not be too surprising, because the human functions of planning and strategy setting are still being argued and have yet to be embraced by mathematics.

Seidenstein and Berbert[43] have examined the extant literature in those areas which they believe comprise the most important "extra" dimensions of teleoperator control:

1. Judging the best path for approaching the target.

2. Approaching the target and minimizing undershoot and overshoot.

3. Orientation of hand for manipulatory task.

4. Final adjustment of arm and hand.

In 1966, Seidenstein and Berbert found essentially no important literature that would give a foundation upon which to build a comprehensive theory of teleoperators. However, their literature review did not encompass K. U. Smith's work and much of the psychomotor theory of perceptual and motor organization (see Bibliography). Some of these theories may ultimately prove extremely useful in teleoperator theory.

Significant direct attacks on the teleoperator problem have been made by Sheridan's group at M.I.T. and Lyman's group at UCLA.[44,45] Both groups bypass the human operator as a planner and strategy formulator. Although man still retains "executive" control of the operation in their approaches, their theories concern only the machine part of the teleoperator in supervisory control situations.

Sheridan compares the different kinds of manual control diagrammatically, as illustrated in Fig. 24. It is the last schematic, representing supervisory control, which focusses the different theoretical approaches. With man out of the loop and with the teleoperator configuration and the environment (including the targets) described in "state space" one can apply some powerful algorithms like those that have been developed for playing chess with computers, finding the quickest route between points, etc. In other words, there is no theory that describes how a human solves a manipulatory problem, but we have developed theoretical approaches which can guide machines while they perform the same problem! If a human is truly a machine, as Wooldridge contends,[46] perhaps we may eventually be able to apply some of these theories to ourselves, and thus improve our own capabilities.

One of Sheridan's students, D. E. Whitney, has completed some pioneering work in the field of supervisory manipulation in state space.[47] He lists the following attributes of a good computer-controlled manipulator, which sound remarkably like the qualities a human manipulator operator must have:

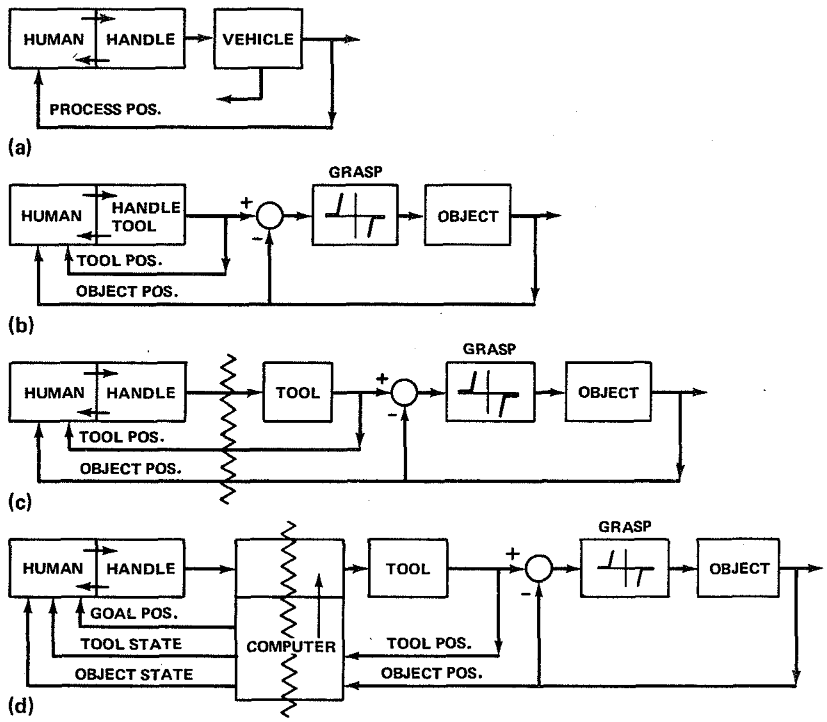


Figure 24 *Comparison of vehicle control and several varieties of manipulator systems. (a) Vehicle control; (b) direct manipulation; (c) remote manipulation; (d) supervisory manipulation.*[44]

1. It employs a symbolic representation or model of the task site. All objects, obstacles, fixed support surfaces and effectors (jaws, tools, etc.) are represented in their proper spatial relationships.

2. It can identify goals in this model. A goal may be thought of as a particular configuration of the objects, obstacles and effectors which the operator wishes to attain.

3. It understands how the effectors can alter the task site as well as how these alterations are represented in the model.

4. It can receive commands which specify goals to be achieved and constraints to be obeyed. Then, using items 1, 2, and 3, it can translate the command into an expanded equivalent. ("Expanded" means that strings of manipulator primitive commands have been substituted for the human primitive command; "equivalent" means that these manipulator primitive commands, when carried out, can be expected to accomplish the previously stated goal.) In other words, the system can make a plan for carrying out the task.

5. It can execute this plan, judging its progress against the plan's expectations, keeping track of its progress by updating the model, and asking for help if trouble develops or things do not go according to the plan.

Suppose the manipulatory task is to move an object from one point to another on a table, avoiding an obstacle on the way (Fig. 25). In state space coordinates this means moving from

$$x(t_0) = \begin{bmatrix} x_0 \\ y_0 \\ 0 \\ 0 \end{bmatrix} \text{ to } x(t_f) = \begin{bmatrix} x_f \\ y_f \\ 0 \\ 0 \end{bmatrix}$$

between time t_0 and time t_f.* The zeroes in the state vectors represent velocity components. The values of x and y, however, must not assume values off the table or too near the obstacle. The best trajectory is found by testing each trajectory between the two points which satisfy the constraints and comparing one against the other using some time, distance, or cost criterion. Problems such as this are common in engineering and are solved by the methods of "optimal control," including the calculus of variations, dynamic programming, etc.[48]

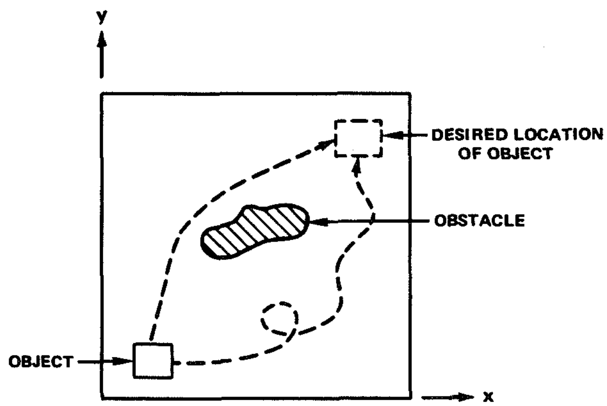


Figure 25 *Diagram showing possible paths around an obstacle in Whitney's state-space approach.*[47]

A more complete recounting of a typical manipulatory task—carrying object A to location X—is shown in Fig. 26. Note that the diagram is basically a computer program and really recapitulates a human operator's

*State space also includes hand position and orientation as well as all features of the environment.

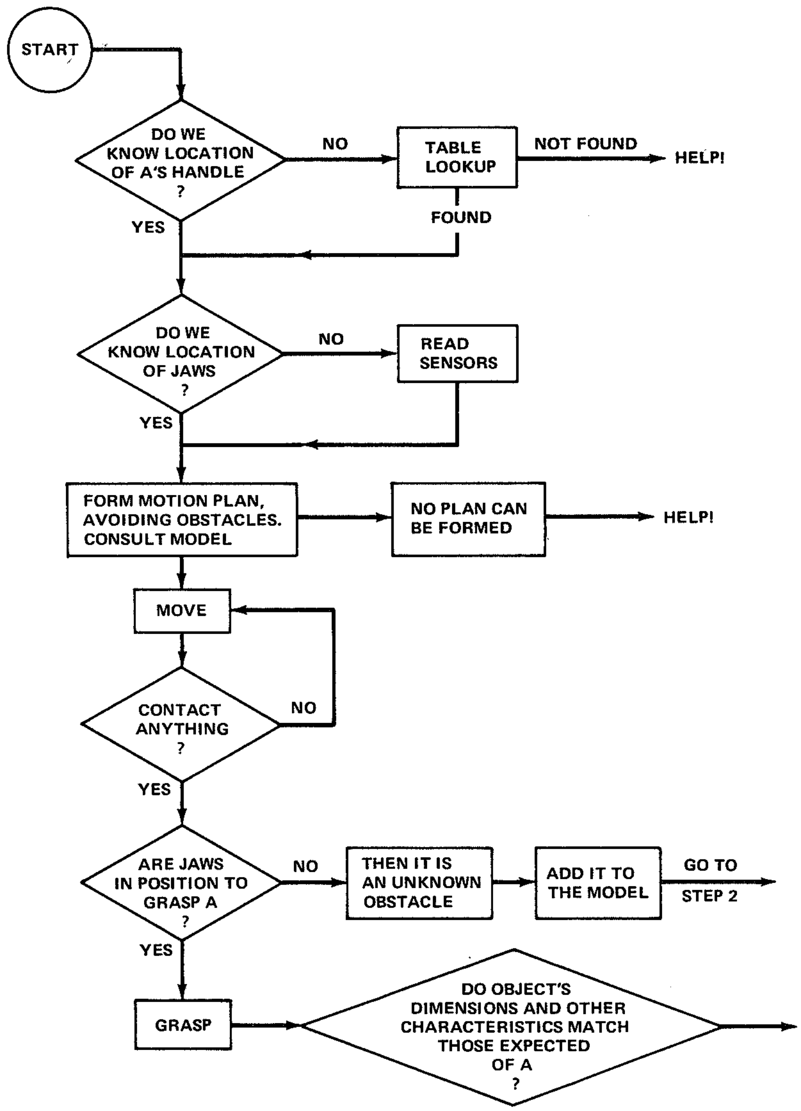


Figure 26 *A possible program for instructing a computer to carry object A to location X.*[47]

unverbalized considerations. Optimal control enters the picture at the point where the motion plan is being formulated.

"Inhibitory control," proposed by Lyman and Freedy,[45] assumes that some paths between initial and final states (teleoperator plus environment) are more likely than others. Our eating motions, for example, are rather stilted, and this is true of most routine manipulatory functions, especially those by wearers of artificial limbs. In inhibitory control, an adaptive controller—probably a computer—would drive the teleoperator between the initial and final states (initially selected by the human controller) along historically favored paths. The human operator monitors the motion and inhibits it where it is in error, due perhaps to a new obstacle placed in the environment. The adaptive controller adds this new information to its running account of favored teleoperator motions; while the human operator still monitors the activity, he is relieved of the burden of planning and detailed execution of the task. This approach differs from that of the M.I.T. group in that human judgment guides the choice of path rather than some optimal control scheme based on minimum time or some other constraint.

APPLICATION OF CONTROL THEORY TO UNILATERAL TELEOPERATORS

Unilateral teleoperators (sometimes called "rectilinear" in error) are controlled by

1. Switches* or potentiometers which actuate motors driving the various degrees of freedom. Feedback in this instance is visual as the operator corrects errors in position and orientation. If switches are used, this control technique is called "rate" or "velocity" control; potentiometers permit variable motor speeds or "proportional rate" control.

2. Replica or prosthetic-type controls that are analogs of the actuator subsystems. The servomotors driving the various degrees of freedom are actuated by an error signal which is proportional to the difference between the desired configuration specified by the controls and the actual configuration of the teleoperator. This is termed "position control."

In any real teleoperator control system, the differential equations describing the motion of the arms, hands, and legs are complicated by the fact that these appendages have mass (which may lead to overshooting the target), have friction in the joints, and may move in an appreciably viscous medium, such as seawater. Such considerations are part and parcel of the design of most control systems, such as those of radar antennas and guns. Thus, the system may be damped to reduce overshooting or "hunting," yet excessive damping will cause undesirably sluggish response. A compromise must be found. The reader should consult texts on control system design.[8] Only a few specialized reports have been published on the application of control theory to specific teleoperators.[15,48]

The just mentioned theory, though well-developed, excludes the most important control-loop component: the human operator. Since we have no

*See Chapter 5 for descriptions of typical control hardware.

practical, analytical way of incorporating the human operator into the teleoperator control equations, conventional control theory remains only a guide. All is not lost, though; because when the mathematics become intractible, insight can frequently be gained by simulating control systems electromechanically. With a human operator plus a reasonable analog of the electrical and mechanical components, different control schemes can be compared, stability regimes can be investigated, and even the analytically elusive properties of the operator can be studied.

Unfortunately, little basic simulator work has been completed. The most significant studies are those by Ritchie, Inc., under Air Force contracts,[43,50] and at General Electric, under DOD sponsorship.[51] The Ritchie simulators employed three and four degrees of freedom and incorporated manipulator arm mass, damping factors, and motor characteristics (Fig. 27). The following conclusions are taken from the Ritchie studies:

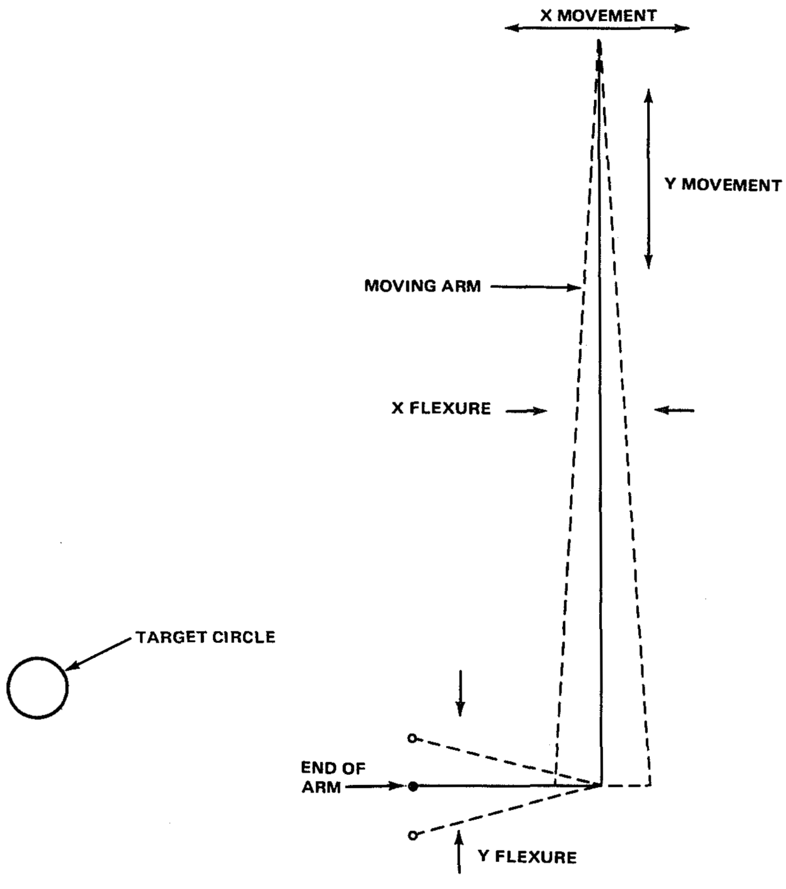


Figure 27 *Sketch of the geometry of one of the Ritchie manipulator simulations.*[43]

1. Proportional rate control is better than fixed rate control and position control in terms of task time required and task efficiency.
2. The use of high speeds in approaching the target resulted in longer fine adjustment times.
3. Small targets require higher travel times than large targets with fixed rate control, but the opposite was found with position control—an "illogical" result.
4. There seemed to be an optimum rate of motion (4 inches/second) for the conditions of the experiment. Overall performance decreased above and below this value.

These kinds of conclusions, one should note, have not yet been extracted from current theory.

At General Electric, R. S. Mosher's group has come to grips with the practical design of the powered exoskeleton, Hardiman I. Hardiman's leg joints are unilateral, while the arm and hand joints are bilateral. To complicate the situation some of the joints are in series. In this section, we briefly describe some of the theoretical studies and simulator work done for the three-joint unilateral case.

Figure 28 illustrates the signal flow diagram for the three joints. The dynamic cross coupling connections are significant because the dynamic feedback to joints 1 and 2 may be positive, creating instability. Note that this feedback is not through the operator or control circuits but rather is a consequence of the series connections of the joints; that is, a jointed, unilateral teleoperator arm could dynamically tear itself apart. General Electric's simulation of this situation indicated that instability could indeed result with the high gains required for control of Hardiman I, and that this instability could be prevented by the addition of proportional, rate, and lag compensation networks.

In the General Electric work we get an inkling of how complicated teleoperator control theory can be even though the human operator was not included in these simulations at all.

APPLICATION OF CONTROL THEORY TO BILATERAL TELEOPERATORS

The first bilateral servoed teleoperators* were built by R. C. Goertz's group at Argonne National Laboratory (ANL) in the early 1950s. Several key theoretical papers originated from this work,[52,53] which was very extensive. We can show only the general approach here. Following Burnett,[54] the

*The common mechanical master-slaves are also bilateral but they are not servoed.

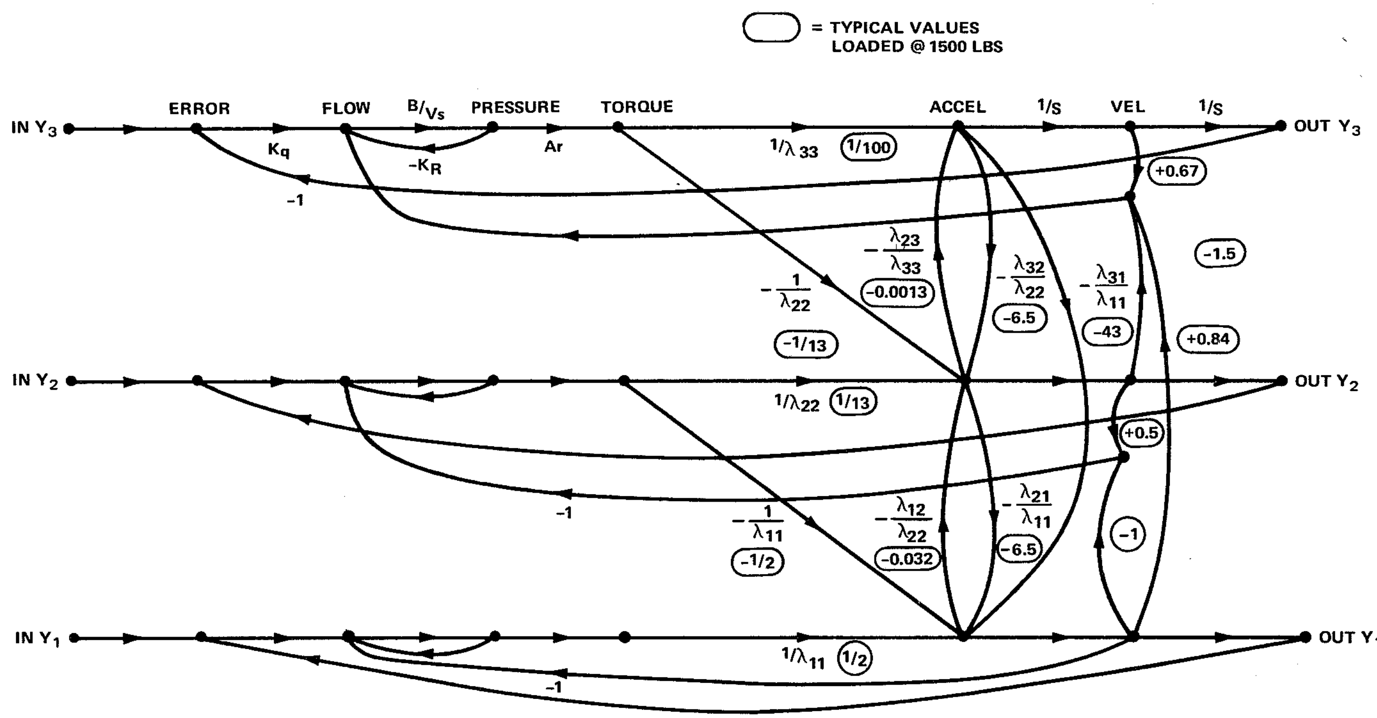


Figure 28 *Signal flow diagram for three unilateral joints in series.*

somewhat idealized symbolic diagram for the ANL Model 2 force-reflecting electrical master-slave manipulator is presented in Fig. 29. The dynamic equations in Laplace transform notations are:

$$T_1 - K_T I = (Js + F)\, s\theta_1$$

$$T_2 + K_T I = (Js + F)\, s\theta_2$$

$$V = K_1\,(\theta_1 - \theta_2) + K_2 s\,(\theta_1 - \theta_2)$$

$$IR = V + K_b s\theta_1 - K_b s\theta_2$$

where J = the motor and gear train inertia
F = the mechanical viscous friction
s = the Laplace transform variable
K_T = the torque constant
K_b = the back EMF constant
T_1, T_2 = externally applied torques
θ_1, θ_2 = angular displacements
R = resistance
I = current
V = voltage
K_1, K_2 = constants defined in Fig. 29

The first two equations are torque equations; they assume linearity and complete bilateral symmetry. The equations represent what is termed a first-order (linear) analysis. Stability is indicated, but higher order (non-linear) analysis could reveal instabilities leading to oscillations.

When bilateral joints are connected in series the analysis gets even more complex. The arms of Hardiman I (Fig. 30) have three such joints. The signal flow and block diagrams are too involved to reproduce here, and the reader is referred to the original General Electric report.[51] In fact, General Electric did not try to analyze the three-joint bilateral model; instead the engineers extrapolated the results of the three-joint unilateral and single joint bilateral cases. The three-joint bilateral model was simulated on an analog computer. It was found that the compensation networks described earlier for the unilateral case also stabilized the bilateral model from 0–1500 pound loads. Teleoperators like Hardiman I are feasible according to the General Electric study; however, during the design process, provisions should be made for adjusting the proportional, rate, lag, and velocity feedback terms over wide ranges.

Apparently, any practical, real-world teleoperator will defy rigorous analysis by virtue of its complexity, at least until better analytical techniques are worked out. The presence of a non-linear, time-varying human operator only worsens the prospects. Thus, the major conclusion of this chapter must be that pure analysis can only guide teleoperator design in terms of

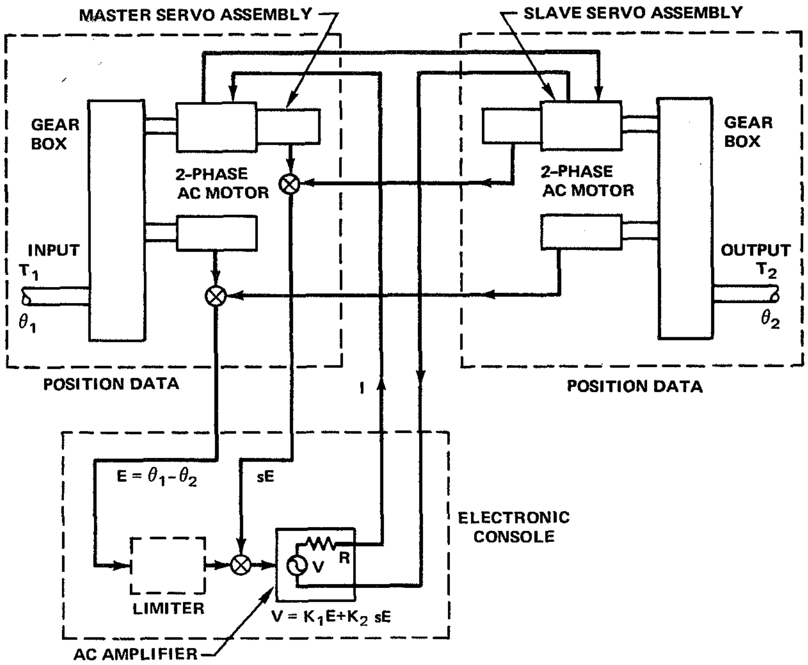


Figure 29 *Symbolic diagram of the force-reflecting servo used in the ANL Model 2 electric bilateral master-slave.*

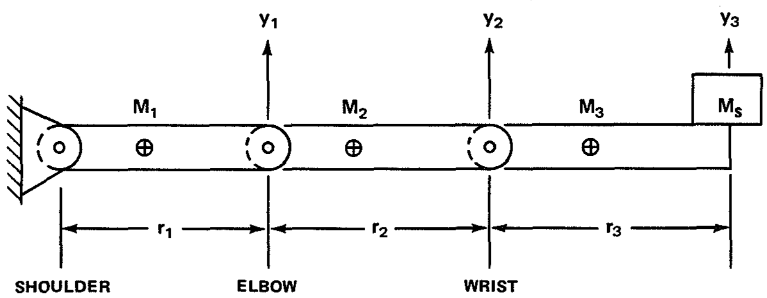


Figure 30 *Sketch of the three-joint teleoperator arm simulated by General Electric in their Hardiman studies. Each of the three joints in the actual man amplifier would be powered and would incorporate force feedback.*[51]

pinpointing design weaknesses and helping the designer think out and grasp the interrelations among control parameters.

The situation is not hopeless because even the three-joint bilateral case can be simulated. Even better is an engineering mockup of the teleoperator with a human at the controls. A good, general approach to teleoperator control design would be threefold: (1) limited analysis; (2) simulation, and (3) engineering mockup.

Chapter 4

THE MAN-MACHINE INTERFACE

THE NATURE OF THE PROBLEM

As computers and other machines assume more and more importance in our lives, the body of literature discussing the *man-machine partnership* and *man-machine symbiosis* grows. In the preceding chapter, it was obvious that the control-theory describing the total man-machine system is rudimentary at best. We try to describe man with the same kinds of equations we use for machines, but success still eludes us. In teleoperator theory, man and machine seem analytically irreconcilable; and to make the schism seem more complete few men doubt that they are superior to machines in many important ways. Yet, man and machine must be integrated, especially in the teleoperator where the partnership is closer than it is in most man-machine systems.

Man and machine meet at two hardware interfaces in the teleoperator: the controls and the displays (Fig. 8). Specific control and display hardware are covered in the next two chapters. In this chapter, the general, more philosophical problems of matching man and machine at these two points will be discussed.

Should we match man to the machine or the machine to man? (This question is overworked in today's literature.) The answer, of course, is that we do both to that degree needed for best teleoperator performance. However, because we still do not understand machines well and know ourselves even less well, this brave plan cannot be consummated easily—and then only very imperfectly. Even in our ignorance, though, we can approach the problem in an orderly fashion by: (1) describing the pertinent properties of man and machine; (2) rationally allotting tasks to one or the other; and (3) building sound bridges across the interfaces at the controls and displays.

DEFINING THE HUMAN OPERATOR AND THE MACHINE

Whenever a subject is either controversial or not amenable to precise description, the literature is abundant; this is the case with man as a controller. Fortunately, a recent and thorough survey of this field has been completed by Serendipity Associates under a NASA contract.[55] We lean heavily on this survey in this chapter, making use of those portions applicable to teleoperators.

We are trying to define the man-machine interface and just where man or machine should assume responsibility in a teleoperator.[5 6] To this end, we list pertinent man and machine attributes side by side for the sake of easy comparison.

Sensory Comparisons

Man	Machine
Senses limited to the ranges and characteristics specified in Tables 5 through 7. However, these limitations do not affect teleoperator control significantly (except in underseas work) because properly designed displays can overcome most limitations.	Sensory ranges extend far beyond those of man. A machine can also sense X-rays and other environmental factors normally invisible to man.
Man's input channel capacities in all senses are limited. They can be saturated easily. He may need machine help at times.	Machine channel capacities can be made as wide as desired at a price measured in power, weight, cost, etc.
Resistant to jamming and noise. Man can often filter out the signals he wishes to use.	Generally more subject to jamming and noise.
Man can sense and recognize patterns, color codings, and written or printed characters. Targets can often be discerned amid noise and clutter.	Pattern recognition possible, but not well-developed yet.
Man is usually considered to be a single-channel detector at any given instant, implying that he must switch his attention from one channel to the other. However, sight, sound and touch usually work together easily in manipulatory tasks.	Machines can handle many channels simultaneously.
Man's sensory capabilities are affected by fatigue, general health, noise, and other environmental factors.	Machines are less affected by the environment and wear.
Man's senses cannot be calibrated reliably in absolute terms to provide quantitative data.	Instruments can be accurately calibrated and easily read. This may be an advantage in delicate manipulations.

Sense Interpretation Comparison

Humans often see only what they expect to see and can be fooled by such things as optical illusion.	Machines are much more literal in their interpretive functions.
If a new, unexpected situation (a new "universe") is encountered, man can cope with it better than a machine. An emergency or accident would fall in this category.	Generally, machines can deal only with the known and expected—the known "universe."

Man's interpretation of data depends upon his previous history with them. Experience is usually beneficial, though it can prejudice an operator.	Historical information can affect interpretation by machine only in those ways which can be implemented by computers; i.e., time averaging, etc.
Man's reliability as an interpreter depends upon his emotional state and fatigue.	Machines are more objective, tireless, and unemotional.
Written language, color codes, and other symbols are readily interpreted. This is particularly useful in handling coded objects.	Languages, codes, and abstract symbols can be interpreted only with difficulty.
Given the symptoms, a human can troubleshoot a malfunctioning teleoperator.	Machines can also do this but only to a limited extent.
The human operator can hypothesize. He can ideate. He can suggest alternative modes of action.	Machines cannot do these things well.
Men are poor monitors of infrequent events.	Machines are much more reliable as monitors.
The human operator is poor at monitoring continuous signals and processes over long periods of time.	Machines are so good at monitoring that some have suggested that they be employed to monitor men instead of vice versa.
Man is good at detecting deviations from normal, particularly in the presence of noise and other signals.	Machines are better than men at monitoring simple processes, but they are less successful when patterns and symbols are involved.

Information Processing Comparison

Relatively low-speed information processor. Essentially a single-channel processor at any instant.	High-speed information processor. Can handle many channels simultaneously.
Weak and inaccurate as a computer. Tires quickly; especially in routine, boring jobs.	Tireless and fantastically accurate in comparison to man. Man should never compute if he can get a machine to do it.
Man is easy to program. He does not require extremely precise instructions. He is *flexible*.	Programming machines is time consuming. Each instruction must be detailed and specific.
Information can be processed in a wide variety of formats. Special coding, punching, etc., not necessary.	Computers are very specific and limited in the forms of information they will accept.
Man's bandpass is about three radians per second. He can transmit 30-35 bits/sec.	A machine's bandpass and data rate can be made much larger than man's—at a price. A machine can thus potentially manipulate much faster than man.
Man's short-term memory is limited in size, accuracy and permanence. Access time is relatively high.	Machine memory can be almost unlimited. Accuracy and performance are high. Access time is very low.

Man processes information so slowly that he is relatively inefficient in search tasks, although he is good at recognizing and identifying targets once they are located.	Machines can rapidly search huge quantities of data for well-defined targets, but accuracy suffers as target definition is worsened.
Man has an excellent long-term memory for related events. Generalized relevant patterns of previous experience can be recalled to solve immediate problems.	This property can be built into machines only at great expense.

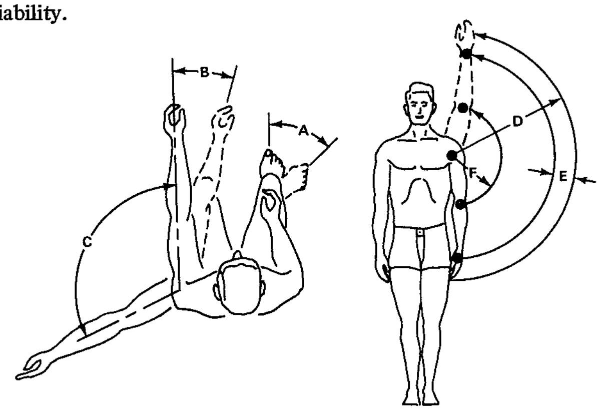
Decision-Making Comparisons

Man can generalize and employ inductive processes.	Machines have less capability for induction and generalization.
A human being does not always follow an optimal strategy—usually because he cannot perceive or examine all ramifications of a situation and cannot compute all the possible solutions.	Machines always follow built-in strategies, or they can compute optimal strategies given sufficient information.
Decisions can be made despite incomplete information and where the rules are not certain.	A computer usually demands complete information before making a decision.
Human decision-making time is relatively high. Often man wavers between alternatives if the decision is not clear-cut.	Machines are fast and specific.
Man is always needed to set priorities, establish values, set goals, risks.	Machines must be instructed as to priorities, values, goals, etc.
Targets of opportunity are recognized better by man.	Machines are relatively insensitive to unspecified opportunities.
Humans can improvise superbly.	Machines improvise poorly.
Man learns from past experience.	Machines can learn, too, but are not proficient at it yet.
Human operators prefer tasks with high degrees of responsibility and authority. Pride and a need to prove "human value" are factors here.	Degrees of responsibility and authority are irrelevant to machine.

Controlling Comparisons

Cannot exert large well-controlled forces. (Force or pressure is man's primary control mechanism.)	Machines can exert considerable force with speed, steadiness, and precision. Reaction time is much smaller than man's.
Superb at manipulation, construction, creative work, non-routine tasks.	Good at routine and well-defined tasks; i.e., those performed under supervisory control.
Tires quickly. Easily bored by routine, repetitive tasks. Man is easy to overload.	Tireless, never bored, hard to overload.

Man's motor output seems to have a bandwidth of about 10 cycles per second, with a natural periodicity (to be avoided) of ½ to 1 cycle per second.	A machine can be designed for almost any bandwidth if one is willing to pay the price.
The motions possible with the human body, though marvelously contrived, are limited in amplitude and articulateness—some motions are impossible, such as telescopic extension of limbs.	In principle, machines are not limited in amplitude and articulateness of motion.
Performs well in emergencies. Can take remedial measures. Man is adaptable and can "reprogram" himself.	Machines do not adapt well to emergencies. They either stop or plod blindly ahead.
Man is often nonlinear in his manipulation of controls.	Linearity or any other function can be built into machine controls.
Humans are highly variable in physique and capability (Fig. 31). Allowance must be made in interface design for this variability.	Machines can be built with fairly well standardized interfaces.



Arm and Foot Movement Limits

Motion	Description	5%ile	50%ile	95%ile	Range (95% of sample)
A	Foot rotation* (side to side)		78°		46°–110°
B	Arm rotation* (side to side)	No data available	48°	No data available	30°–66°
C	Arm rotation* (side to side)		134°		100°–168°
D	Arm reach radius†	27.7"	30.0"	32.3"	No
E	Wrist reach radius†	7.0"	7.6"	8.2"	data
F	Elbow reach radius†	16.5"	18.0"	19.4"	available

*Air Force personnel.
†Industrial workers.

Figure 31 *Some arm and foot movement limits of use in designing anthropomorphic controls.*

Table 5—Man's Senses As Informational Channels: A Comparison of the Intensity Ranges and Intensity Discrimination Abilities of the Senses*

	Intensity Range		Intensity Discrimination	
Sense	Smallest Detectable	Highest Practical	Relative	Absolute
Vision	2.2 to 5.7 x 10^{-10}	Roughly, the brightness of snow in the midday sun, or about 10^9 times the threshold intensity	With white light, there are about 570 discriminable intensity differences in a practical range.	With white light, 3 to 5 absolutely identifiable intensities in a range of 0.1 to 50 millilamberts.
Audition	1 x 10^{-9} ergs/cm^2	Roughly, the intensity of the sound produced by a jet plane with afterburner or about 10^{14} times the threshold intensity	At a frequency of 2,000 cps, there are approximately 325 discriminable intensity differences.	With pure tones about 3 to 5 identifiable steps.
Mechanical vibration	For a small stimulator on the fingertip, average amplitudes of 0.00025 mm can be detected.	Varies with size of stimulator, portion of body stimulated and individual. Pain is usually encountered about 40 db above threshold	In the chest region a broad contact vibrator with amplitude limits between 0.05 mm and 0.5 mm provides 15 discriminable amplitudes	3 to 5 steps
Touch pressure	Varies considerably with body areas stimulated and the type of stimulator. Some representative values: Ball of thumb–0.026 ergs Fingertips–0.037 to 1.090 ergs Arm–0.032 to 0.113 ergs	Pain threshold	Varies enormously for area measured, duration of stimulus contact and interval between presentation of standard and comparison stimuli	Unknown

Kinesthesis	Joint movements of 0.2 degree to 0.7 degree at a rate of 10 deg/min can be detected. Generally, the larger joints are the most sensitive	Unknown	No data available	No data available
Angular acceler-ation	Dependent on the type of indicator used 1. Skin and muscle senses 1 deg/sec^2 2. Nystagmic eye movements 1 deg/sec^2 3. Oculogyral illusion 0.12 deg/sec^2	Unconsciousness or "black-out" occurs for positive "g" forces of 50 to 8 g lasting 1 second or more Negative forces of 3 to 4.5 g cause mental confusion, "red-vision" and extreme headaches lasting sometimes for hours following stimulation	No data available	No data available
Linear accel-eration	In aircraft–0.02 g for accelerative forces and 0.08 g for decelerative forces	For forces acting in the direction of the long axis of the body, the same limitations as for angular acceleration apply.	No data available	No data available

*Adapted from Ref. 55.

Table 6—A Comparison of the Frequency Ranges and Frequency Discrimination Abilities of Some of the Senses*

Sense	Wavelength or Frequency Range		Wavelength or Frequency Discrimination	
	Lowest	Highest	Relative	Absolute
Vision (hue)	300 mμ	1,500 mμ	At medium intensities there are about 128 discriminable hues in the spectrum	12 to 13 hues
Interrupted white light	Unlimited	At moderate intensities and with a duty cycle of 0.5, white light fuses at about 50 interruptions per second	At moderate intensities and with a duty cycle of 0.5, it is possible to distinguish 375 separate rates of interruption in the range of 1 to 45 interruptions per second	No greater than 5 or 6 interruption rates can be positively identified on an absolute basis.
Audition (pure tones)	20 cps	20,000 cps	Between 20 cps and 20,000 cps at 60 db loudness, there are approximately 1,800 discriminable steps	4 to 5 tones
Interrupted white noise	Unlimited	At moderate intensities and with a duty cycle of 0.5, interrupted white noise fuses at about 2,000 interruptions per second.	At moderate intensities and with a duty cycle of 0.5, it is possible to distinguish 460 separate interruption rates in the range of 1 to 45 interruptions per second.	Unknown
Mechanical vibration	Unlimited	Unknown, but reported to be as high as 10,000 cps with high intensity stimulation.	Between 1 and 320 cps, there are 180 discriminable frequency steps.	Unknown

*Adapted from Ref. 55.

Table 7—Characteristics of the Senses*

Parameter	Vision	Audition	Touch	Vestibular
Sufficient stimulus	Light-radiated electromagnetic energy in the wavelengths from 400 to 700 mμ (violet to red)	Sound-vibratory energy, usually airborne 20 cps to 20,000 cps	Tissue displacement by physical means >0 to <400 pulses per second	Accelerative forces Linear and rotational accelerations
Spectral range	120 to 160 steps in wavelength (hue) varying from 1 to 20 mμ.	~3 cps (20 to 1000 cps) 0.3 percent (above 1000 cps)	$\frac{\Delta pps}{pps} \simeq 0.10$	
Dynamic range	~90 db (useful range) for rods = 0.00001 mL to 0.004 mL; cones = 0.004 mL to 10,000 mL	140 db (0 db = 0.0002 dyne/cm^2)	~30 db, 0.01 mm to 10 mm	Absolute threshold $\simeq 0.2^\circ$/sec/sec
Amplitude resolution $\left[\frac{\Delta I}{I}\right]$	contrast $= \frac{\Delta I}{I} = 0.015$	0.5 db (1000 cps at 20 db or above)	0.15	~0.10 change in acceleration
Acuity	10 arcminutes	Temporal acuity (clicks) $\simeq 0.001$ sec	Two-point acuity = 0.1 mm (tongue) to 50 mm (back)	
Response for rate for successive stimuli	~0.1 sec	~0.01 sec (tone bursts)	Touches sensed as discrete to 20/sec	~1 to 2 sec nystagmus may persist to 2 min after rapid changes in rotation
Reaction time for simple muscular movement	~0.22 sec	~0.19 sec	~0.15 sec (for finger motion, if finger is the one stimulated)	

Best operating range	500 to 600 μ (green-yellow) 10 to 200 foot-candles	300 to 6000 cps 40 to 80 db		1 g acceleration directed head to foot
Indications for use	1. Spatial orientation required. 2. Spatial scanning or search required. 3. Simultaneous comparisons required. 4. Multidimensional material presented. 5. High ambient noise levels.	1. Warning or emergency signals. 2. Interruption of attention required. 3. Small temporal relations important. 4. Poor ambient lighting. 5. High vibration or g forces present.	1. Conditions unfavorable for both vision and audition. 2. Visual and auditory senses.	1. Gross sensing of acceleration information.

*Adapted from Ref. 55.

DEFINING THE MAN-MACHINE INTERFACE

Given the attributes of man and machine, how does one draw the interface between them? In practice, this question is answered by allocating tasks or portions of tasks to each. The type of machine and the job to be done are important in determining how much man and how much machine will be employed in control. Not too surprisingly, the personal philosophy of the designer has something to do with establishing the interface: Some engineers believe computers should be brought in for supervisory and preview control, others want men in the loop at all times. Finally, no matter how carefully control tasks are apportioned between man and machine, the match will never be perfect.

To paraphrase the Biblical quotation: Render unto the machine the things that are the machine's. In the very specific area of teleoperator control, the problem of task allocation is rather simple because today's teleoperator normally works with the human operator in *full real-time* control of *all* activity; that is the operator usually renders nothing to the machine in terms of control. Of course, much of the sensing and actuating is done by machine, but no direct control functions are carried out unless the operator takes himself out of the loop and institutes a subroutine. Excluded from this generalization are the many *local* control loops that exist in any sizeable machine.*

When the first master-slaves were developed in the late 1940s, the human operator was essentially in full control of every operation—lifting, moving, pouring, manipulating. In fact, the word master-slave is rather contemptuous of the machine role in the man-machine partnership. Before long, however, drills, saws, hammers, and other tools were being used in the same way man uses them. In other words, the human operator began to depend upon the machine for laborious "subroutines." No one thought to call a slave-held drilling operation a subroutine, but nevertheless the operator did relinquish part of the control task to the machine. Tools have become more and more important in the effective application of teleoperators; and the most important of these tools is the general-purpose digital computer. The computer is somewhat like man in the way he thinks, but it is undeniably on the other side of the man-machine interface.

Few systematic objective rationales exist for drawing the man-machine interface. Obermayer and Muckler have classified past attempts into five categories or, more properly, philosophies:[57]

1. Automate wherever the task can be described in sufficient detail for engineering design, even though man might do some of these tasks better. Under this philosophy, man is assigned poorly defined and complicated tasks. Result: poor use of both man and machine.

*Thermal control loops, for example.

2. Follow traditional roles and preferences, wherein man serves as the prime controller of vehicle attitude and power (as on aircraft). This approach has generally been discredited as man-machine systems have become more powerful and complex.

3. Assume specific human capabilities and limitations and design to make the best use of man under these conditions. Usually, this has been interpreted to mean that man should be used only as a narrow-band, simple amplifier. In teleoperator work, man is obviously much more than this, being a strategist and decision-maker as well as a supplier of control forces.

4. Assume a formal mathematical model of man (a human transfer function) and design the control system as if man were a completely specified servo element. As demonstrated in Chapter 3, this approach is hardly applicable to teleoperator design.

5. Make a direct empirical assault on the system with simulators. Because some teleoperators are so complex; viz., Hardiman; this is occasionally done.

None of these five approaches really suffices for teleoperator design; they do not take into account man's most essential attributes—planning, decision-making, etc.,—all difficult to reduce to equations.

A systematic, logical approach to defining man's place in a large man-machine complex has been proposed by Serendipity Associates.[55] This rationale, which is summarized in Table 8, is basically a checklist of "activities" that a control system designer must consider in allocating tasks between man and machine. It is this allocation of tasks, of course, which really defines the man-machine interface. The rather subjective thinking-it-out approach of Serendipity Associates infers that the location of this interface could depend largely upon who is doing the thinking. For example, a young engineer brought up in a computer environment might naturally lean toward

Table 8—A Possible Sequence of Activities for Assigning Tasks to Man and Machine*

ACTIVITIES FOR DETERMINING THE OPTIMAL ROLE OF MAN

Activity 1
Hypothesize the Potential Basic Role of Man

Outputs

1. Statements proposing unique human capabilities to foster system performance.
2. Statements proposing man-rated core performance to foster system performance.
   a. Sensing
   b. Interpreting
   c. Information Processing

d. Decision-Making
e. Controlling
f. Monitoring
g. Information Storage

Activity 2
Hypothesize Potential Complementary and Support Role of Man

Outputs

1. Statements proposing utilitarian human capabilities to foster complementary system performance.
2. A check list of personnel support system needs:
   a. Human Maintenance
   b. Human Monitoring
   c. Life Support
   d. System Protection

Activity 3
Review Manned System Solution Feasibility

Outputs

1. Statements identifying suspect areas of compatibility between human variables and system parameters which would eliminate a manned system solution from further consideration.
2. Statements identifying suspect areas of effectiveness or practicality which would eliminate a manned system solution from further consideration.

Activity 4
Develop a Preliminary Operator Concept

Outputs

1. A summary of operator performance in the local and remote segments for operations, maintenance, and support.
2. Estimates of the number of operators.
3. Summary of concepts for operator performance achievement and proficiency maintenance.
   a. Selection
   b. Training
   c. Job Aids
   d. Human Engineering
   e. Proficiency Maintenance

Activity 5
Analyze Personnel Support Requirements

Outputs

1. Statements and supporting data of personnel support system requirements and development of operational implications.

Activity 6
Review Potential Operator Role for Acceptance and Reliability

Outputs

1. Summary statements of acceptability of manned system concept indicating areas of possible lowered reliability due to unacceptable role requirements.

Activity 7
Synthesize Optimal Operator Role

Outputs

1. Description of an optimal operator role including the operator concept, personnel support requirements, and operator effectiveness.

ACTIVITIES FOR DETERMINING THE OPTIMAL ALLOCATION OF FUNCTION

Activity 8
Establish Feasibility of Man-Rated Allocation

Outputs

1. Statements and rationale supporting the feasibility or unfeasibility of a man-rated allocation for function performance.

Activity 9
Develop Potential Man-Rated Allocations

Outputs

1. Descriptions of alternative man-rated allocations varying in extent of man participation for each function.

Activity 10
Review Allocation Poential Against Psychophysical Capacities

Outputs

1. Statements and data identifying allocations which are unfeasible because of incompatibility with basic psychophysical capacities.

Activity 11
Review Allocation Potential Against System or Function Constraints

Outputs

1. Statements and data identifying allocations which are unfeasible because of system environmental constraints.
2. Statements and data identifying allocations which are unfeasible because of system or function performance constraints.

Activity 12
Review Allocation Potential Against Human Reliability

Outputs

1. Statements and data identifying allocations which are unfeasible because of suspect human reliability.

Activity 13
Synthesize Man-Rated Allocations

Outputs

1. A summary and preferred order of potential man-rated solutions for accomplishment of each function.

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*Adapted from Ref. 55.

mechanizing control tasks that an old-timer would assign to a human operator. This ambiguity in task allocation and the location of the man-machine interface is also inherent in the long but rather fuzzy list of man-machine attributes appearing earlier in this chapter.

In the context of future teleoperator design, the man-machine interface seems to be moving in the direction of letting the machine do more of the work. The following general assertions emphasize this trend and also offer some general guidelines relative to establishing the man-machine interface in teleoperators.

Assign to Man These Control-Oriented Tasks:

Pattern recognition
Target identification
New, exploratory manipulation
Long-term memory
Trouble-shooting, emergency operation
Hypothesizing, ideation, planning
Interpreting variable format data
Inductive thinking
Setting goals, priorities, evaluating results

Assign to Machine These Control-Oriented Tasks:

Monitoring multichannel inputs
Boring, repetitious manipulation
Precision motions and precision force applications
High-speed motions, particularly oscillatory
Short-term memory
Computing
Monitoring

Deductive analysis
Development of optimal strategies
Non-anthropomorphic motions

The tendency today is unquestionably to let the machine portion of the teleoperator do the hard, repetitious work, while the human thinks, plans, and explores. As machines become better able to identify and manipulate targets in accordance with man's general instructions, the machine will take over even larger portions of the control task.

The philosophy of applying machine (computer) control wherever reasonable has a profound effect upon the design of displays and control hardware. If man is to adopt more and more the function of an executive, he will need more executive-type controls; that is, controls that switch in subroutines. A specific subroutine could be initiated by a switch, a coded signal, or even voice command. Supervisory controls, therefore, are abstract and far-removed in terms of spatial correspondence from the master arm of a master-slave manipulator. The more "intelligent" the machine, the more abstract the controls and the less often man would enter the control loop to operate the controls directly. At the far end of the spectrum—where the true robots dwell—today's crude anthropomorphic master arms and hands would be replaced by general verbal instructions.

BRIDGING THE INTERFACE

Once control tasks have been divided between operator and machine, there remains the "communication problem," which means insuring that man can command the machine efficiently and that the machine can feed back information to man with ease. The two points of contact where matching is necessary are at the displays (machine output) and the controls themselves (man's output) (Fig. 8).

For effective control of the teleoperator, many engineers believe that the controls should be organized like man; that is, be anthropomorphic—a true extension of man. This interface-bridging philosophy is different from, if not opposed to, the school that wants to make fuller use of machine capabilities and supplants anthropomorphic controls with switches that initiate machine-controlled subroutines. Obviously, the more the machine is in command, the less anthropomorphic the controls need to be. In hardware, these two philosophies are represented by the ANL electric master-slaves with slaved TV display on one hand and the largely computer-controlled manipulators at Case Western Reserve and M.I.T. on the other. In between are a few manipulators displaying various combinations of anthropomorphism and the more abstract, symbolic controls. This bifurcation of the field is becoming more evident each day.

There are undeniable advantages in anthropomorphism and spatial correspondence,* the two prime tenents of the make-the-machine-like-man school:

1. An operator can use skills learned in everyday life to run the machine.

2. Operation is natural, not abstract, and requires less training.

3. Tasks requiring a high degree of physical coordination are often possible; e.g., hula-hooping.

4. The teleoperator is "generalized," like the human operator, and is readily adaptable to many varied tasks.

5. The operator "feels at home." He identifies himself better with the task.

6. It is suspected but not objectively proven that an operator's reactions in emergencies are quicker and more effective.

The computer-oriented school employs man's higher powers—planning, decision-making, etc:—and matches these abstract outputs to the machine using codes understood by the machine. Using today's technical vernacular, the first philosophy matches hardware to the human; the second matches software to the human. Some advantages and disadvantages of an abstract, software dialog are:

1. Abstract language can communicate more control information per unit time to the machine.

2. Nonanthropomorphic commands, such as wrist rotation, can be given.

3. Man is not "wasted" in dull, routine tasks and can use his higher faculties to do a better job.

4. The abstract language is usually highly specialized and may not meet the requirements of the task, especially an emergency.

5. Repetitive tasks can be done with high speed.

We have discussed so far matching the machine to the human operator; perhaps the operator is malleable too. Operator selection and training can help bridge the man-machine interface. Operators should be selected with the same care as for jet pilots. Factors such as depth perception, eye-hand coordination, and reaction time are important in the operation of contemporary master-slaves. Good physical condition is also a prime requisite because remote manipulation is arduous, demanding work. Training with manipulators or simulated tasks is essential. Although a few minutes with a master-slave can give a novice a good feel for the machine, only many months

*Spatial correspondence exists when a motion by the human controller is duplicated by the machine.

of experience will make a good operator. At the other end of the teleoperator spectrum, one would suppose that operating a teleoperator possessing a large array of subroutines would require high analytical power and abstract reasoning capabilities. But none of these man-and-computer-controlled teleoperators has been used operationally as yet.

Summarizing this chapter, we note that the man-machine interface is at best a poorly drawn boundary between man and machine, particularly in teleoperators. It is a dynamic boundary that changes with the application, with the machine state of the art, and even with the personal philosophy of the teleoperator designer. There is no detailed, well-defined, objective rationale that tells a designer how to deal with the man-machine interface. There are rules-of-thumb, opinions, and checklists for thinking out the problem. Basically, the field of teleoperator design is too young for hard and fast rules. Despite the lack of rigor evident above, the man-machine interface has been surmounted many times in many ways during the past two decades. In the next two chapters, we relate some of the solutions—past, present, and future—in terms of control and display hardware.

Chapter 5

TELEOPERATOR CONTROLS

AN OVERVIEW

The fundamental function of switches, joysticks, and other control hardware is to translate the commands of the operator into signals that can be understood by the machine portion of the teleoperator. In control engineer's language, a control is really a transducer—a device that converts a signal from one form to another; for example, the force on a joystick to a proportional voltage operating a motor. The signals generated by the control hardware may be simply proportional to some physical input from the operator, or they may be symbolic; that is, they may contain coded meanings, such as move from point A to point B. A simple symbolic input, perhaps generated by a typewriter, can release a subroutine containing a long train of "primitive," low-level signals to the teleoperator's basic actuators.

Man's signals to his machines are usually generated by his hands. Direct force activates most teleoperator controls, including those that switch in subroutines via a teletypewriter. Force and pressure from man's appendages also configure complex controls, such as analog or replica controls, or activate arrays of switches in complex patterns. In some cases, particularly in the medical field, control forces are created by the feet, the tongue, the head, and various muscles throughout the body. Man also generates more subtle outputs; eye movements, muscle bulges, and electromyographic signals from electrodes attached to the body are used for control purposes. Finally, the human voice can carry a heavy traffic of control information if we can find a machine that can listen and interpret properly.

Regardless of how the human body creates control signals, they can be classified into four types:

1. On-off signals, which may simply activate a motor or perhaps begin a long, complicated subroutine.
2. Proportional signals, which might control the speed and direction of a motor.
3. Configuration signals, where an input control device is placed in a specific configuration by the human operator. The device then generates signals representative of this configuration and the teleoperator actuators try to attain the stipulated configuration. Often this kind of control is termed *position control.* It is employed in many master-slaves, exoskeletons, and walking machines.
4. Symbolic signals, with intrinsic, coded meaning.

Using the above classifications and the various types of physical controls associated with teleoperators, we can construct the matrix shown in Table 9. Most of the more sophisticated teleoperators, it will be noticed, utilize configuration (position) control. In most cases, the control configurations are

Table 9—Overview of Control Hardware

Basic type of control	Hardware manifestations	Types of teleoperators using control type
On-Off	Various switches (hand, eye, voice, muscle bulge, EMG)	Unilateral manipulators, artificial limbs, lunar surface samplers
Proportional	Potentiometers, joysticks, voice, muscle-bulge devices, EMG controls	Unilateral manipulators, artificial limbs
Configuration	Cables, potentiometers, servos (all located on the analog)	Bilateral manipulators, walking machines, exoskeletons
Symbolic	Typewriters, voice, punched cards, other software, switches	All teleoperators that employ supervisory control subroutines

those taken by the human body; but this is not always true—analog controls may assume decidedly nonanthropomorphic shapes.

SWITCHES AND SWITCHBOXES

The simplest teleoperator control is the on-off switch. Many hundreds of unilateral manipulators now working in hot cells and on submersibles are controlled from switchboxes and switch consoles. The advantages of the switch are many: simplicity, low cost, reliability, no load reflected to tire the operator, and switchboxes can be made small and portable, just the thing to carry from porthole to porthole within a cramped submersible. There are accompanying disadvantages, too. Switches are open-loop controls; there is no force feedback. Unless potentiometers or multiple-pole switches are used, there is no control over the rate of teleoperator joint movement. Only one joint can be activated at any instant during precision manipulation. (Some fast slewing motions can be carried out using more than one degree of freedom.) Lastly, switch arrays bear little resemblance to the manipulator configuration; they are decidedly nonanthropomorphic; and operator identification with the task is small. Nevertheless, in many applications, simplicity, reliability, compactness and low cost win out.

On-off switch control may be attained with toggle switches, push-button switches, or slide switches. If rate control is also required, a separate potentiometer can be connected in series with the switches. Often, however, proportional control of manipulator joint movement is achieved by installing rotary or linear potentiometers as the primary control elements. Pressure-sensitive resistance elements, strain gauges, and piezoelectric elements can also provide an output proportional to the force applied by the operator. Proportional controls are usually spring-loaded so that they return to a null position when the operator removes his hand. Most on-off push-button and lever-type switches also return to zero when released. Actually, manipulator joint motion is "three-valued;" that is, *left/stop/right* or *counterclockwise /stop/clockwise.* The corresponding control switches are also three-valued. Three-way toggle switches (Fig. 32) are common and so are pairs of spring-loaded push buttons (Fig. 33).

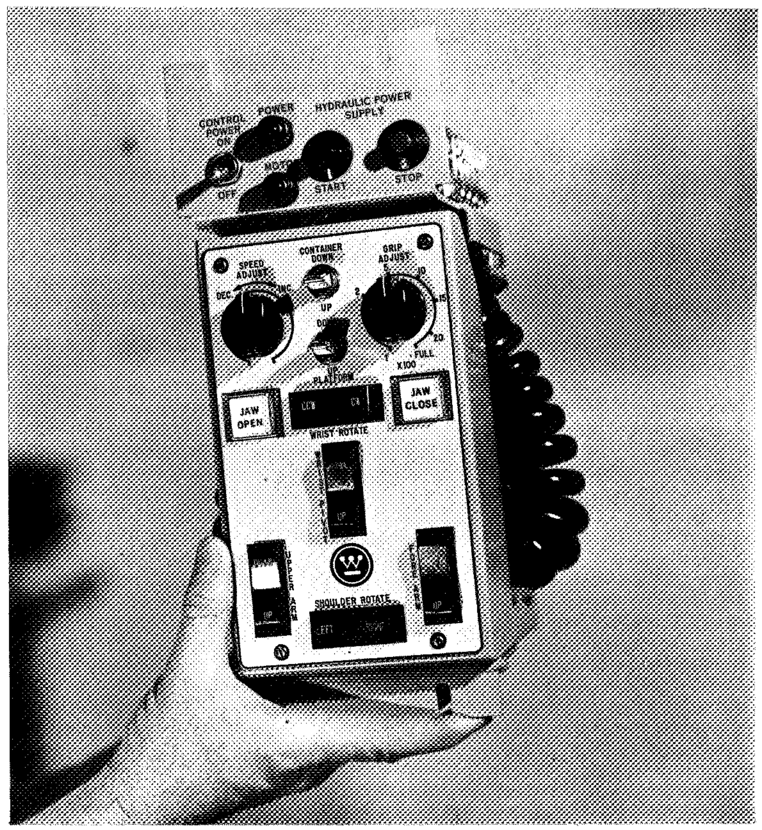

Figure 32 *A control box for an underseas electrohydraulic unilateral manipulator. Most switches are three-way. (Courtesy of Westinghouse Electric Corp.)*

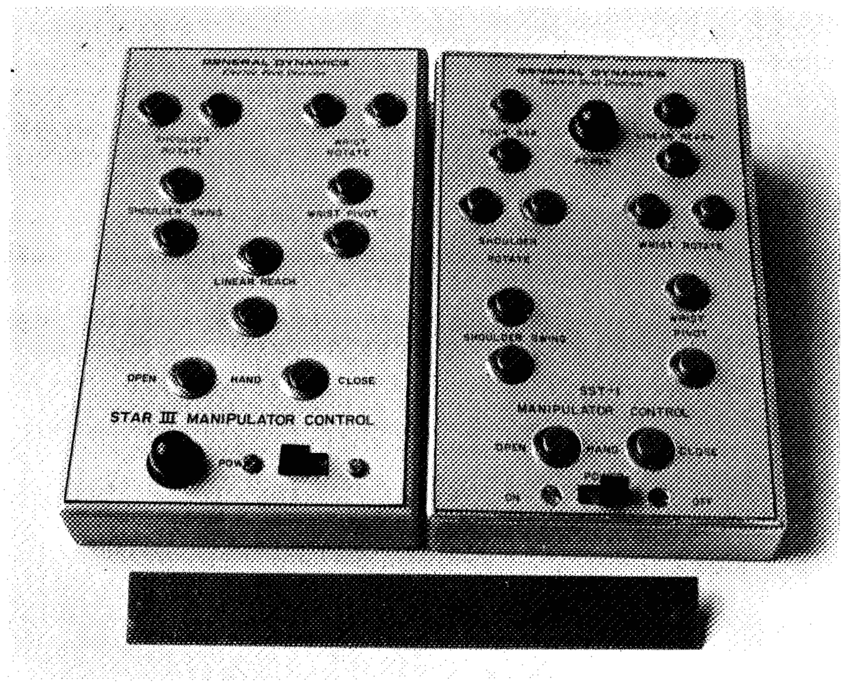

Figure 33 *A push-button control box for an underseas electrohydraulic unilateral manipulator. (Courtesy of Electric Boat Division, General Dynamics.)*

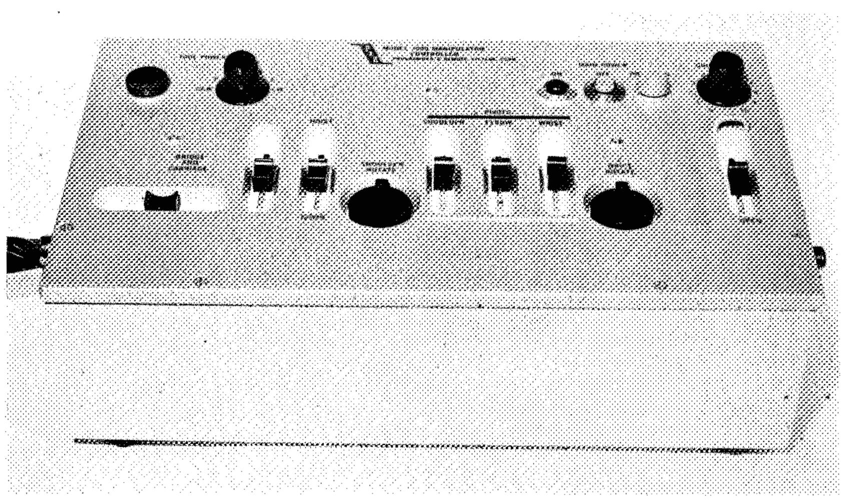

Figure 34 *The switchbox for the PaR 3000 unilateral electric manipulator. Note the three-position switches for some pivots. (Courtesy of PaR.)*

Switchboxes or control arrays are arrays of on-off switches, potentiometers, and feedback signals arranged in a convenient, logical fashion (Fig. 34). There will be one switch or pair of switches for each teleoperator degree of freedom. Switches may be color-coded; coding by shape is also common because the operator should keep his eyes on his work rather than the switchbox. To build in a little anthropomorphism, three-valued switches are connected to move a joint to the right when the switch is moved to the right and vice versa; ditto with up-and-down motion and rotary motion.

Switches and potentiometers usually connect directly with the electric motors that drive the joints in all-electric teleoperators. In electrohydraulic and electropneumatic teleoperators, switch controlled electrical signals open and close valves (Fig. 35). When the teleoperator is far away from the control station, the control signals may be time-multiplexed, as is common in conventional remote control. In space work, the control signals may be digitized before transmission, as described below for the Surveyor surface sampler.

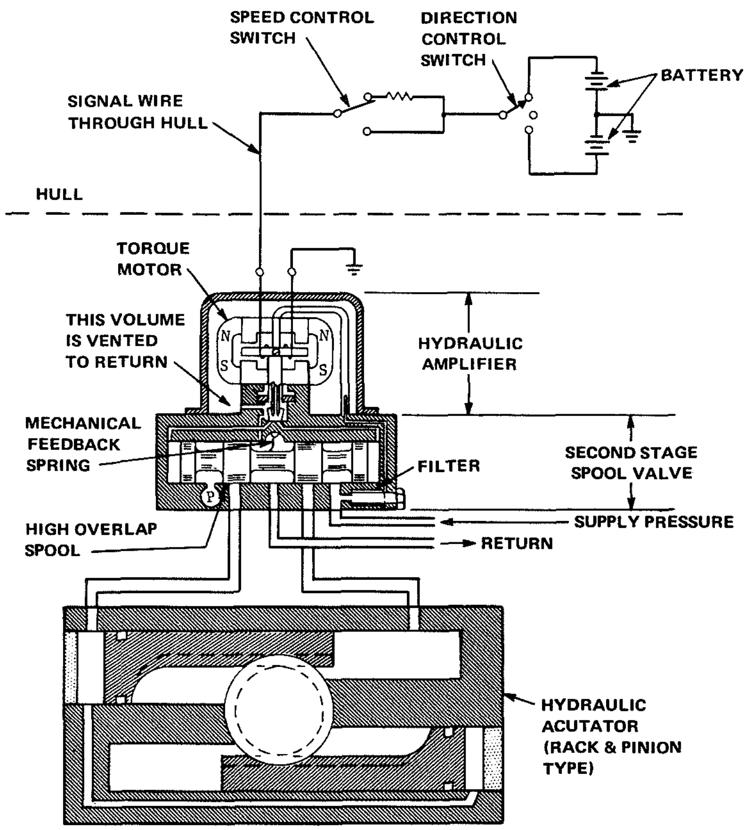

Figure 35 *A typical unilateral electrohydraulic control circuit. (Courtesy of Westinghouse Electric Corp.)*

The NASA-JPL Surveyor surface samplers, while not particularly dexterous teleoperators, did carry out many lunar experiments during which they manipulated lunar soil and rocks. In one instance, a surface sampler was used to dislodge a Surveyor alpha-scattering experiment which was hung up on the spacecraft—a classic example of the use of a teleoperator for repair in a distant, hostile environment.

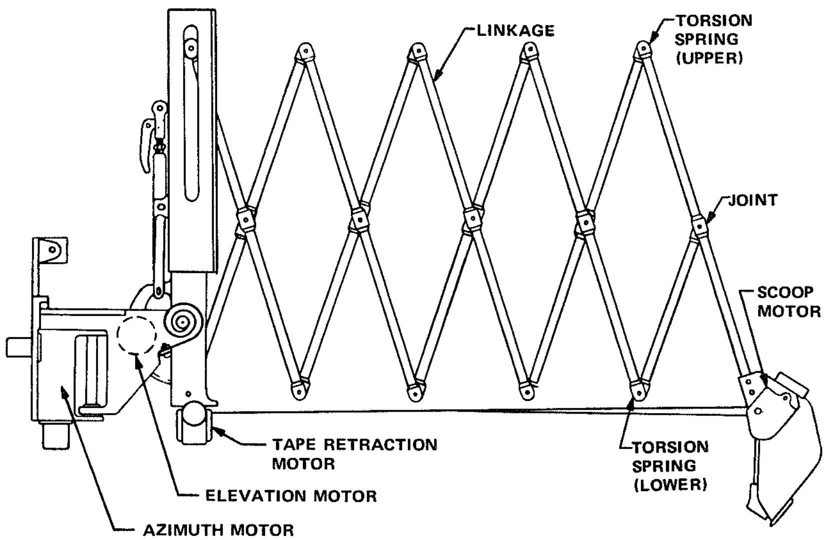

Figure 36 *The Surveyor surface sampler in extended position. There are only four degrees of freedom.*[58]

The sampler's four degrees of freedom were driven by reversible motors (Fig. 36) activated by digital commands dispatched from NASA's Goldstone Deep Space Network station in California. The only feedback to the operator consisted of television pictures (delayed by the signal transit time of about 1.3 sec) and telemetry signals indicating the current delivered to the motor being operated. Only one motor could be activated at a time—and then only in 2- or 0.1-second increments. Except for this quantization of motion, the surface sampler operated much like a unilateral manipulator in a terrestrial hot cell.

The sampler controls, however, were not the simple switches we associate with unilateral manipulators. The operator had to send digital commands to activate the proper motors, as indicated in Table 10. The selection of the digital command word is analogous to selecting a switch on a switchbox and pressing it. The operator could also select, using additional commands, the length of the time the motor would run (2 or 0.1 sec) and the number of motion increments allowed. Thus, the operator could watch his television

Table 10—Output Commands from the Surveyor Surface Sampler Command Encoder*

No.	Digital word	Command	Destination	Function
1	1101 (or) 0101†	Squib-enable ON	Low-power latch	"Arms" or enables squib-firing circuit
2	1111	Squib-enable OFF	Low-power latch	"Disarms" or disables squib-firing circuit
3	0011	Release mechanism	Squib-firing circuit	Provides power to activate pin-puller squib and unstow the mechanism
4	0000	Coarse-timing mode	Low-power latch	Sets 2-sec timing mode for motors
5	0111	Fine-timing mode	Low-power latch	Sets 0.1-sec timing mode for motors
6	0001	Extend	Motor switch	Provides power to extension-retraction motor to extend mechanism
7	0110	Retract	Motor switch	Provides power to extension-retraction motor to retract mechanism
8	1011	Rotate left	Motor switch	Provides power to azimuth motor to rotate mechanism to the left
9	1100	Rotate right	Motor switch	Provides power to azimuth motor to rotate mechanism to the right
10	1001	Open scoop	Motor switch	Provides power to scoop motor to open scoop door
11	1110	Close scoop	Motor switch	Provides power to scoop motor to close scoop door
12	0100	Elevate	Motor switch	Provides power to elevation motor to rotate mechanism upward
13	0010	Lower	Motor switch	Provides power to elevation motor to rotate mechanism downward
14	1000	Disengage clutch	Solenoid switch	Provides power to elevation clutch solenoid to disengage elevation drive
15	1010	All motors OFF	Motor solenoid control	Turns off power to motors and clutch solenoid

*Adapted from Ref. 59.
†Redundant command.

Table 11—Surface Sampler Command Tape 901*

Minor sequence number	Surface Sampler command
3150	Squib enable
3151	Squib enable backup
3152	Release mechanism
3153	Extend four 2-sec steps
3154	Extend five 2-sec steps
3155	Retract one 2-sec step
3156	Lower one 2-sec step
3157	Elevate one 2-sec step
3250	Lower two 2-sec steps
3251	Rotate left two 0.1-sec steps
3252	Rotate right eight 0.1-sec steps
3253	Lower ten 0.1-sec steps
3254	Elevate two 2-sec steps
3255	Rotate left one 2-sec step
3256	Extend six 2-sec steps
3257	Rotate right one 2-sec step
2450	Open scoop N 0.1-sec steps
2451	Retract two 2-sec steps
2452	Close scoop N 0.1-sec steps

*Ref. 58.

monitor and proceed stepwise through his experiment using the move-and-wait strategy recommended for time-delay situations.

Preprogrammed tapes were also employed for some sampler motions, providing a form of supervisory control. This subject will be covered in more detail toward the end of the chapter; a typical series of preprogrammed commands used for the surface sampler will suffice here (Table 11). The preprogrammed tapes reduced the burden on the operator considerably during surface sampler operation.

JOYSTICKS

A joystick is a stick-like control that may be tilted forward and backward, sideways; it may also be twisted or pushed in and out along its axis. Buttons and switches are frequently mounted within reach of the operator's fingers while he is manipulating the stick. A joystick consolidates controls for several degrees of freedom into a single piece of hardware. Two important features of joystick control are proportionality (joystick displacement or pressure can be employed for rate control of a joint) and directionality (joint motion can be reversed simply by reversing the joystick polarity). The joystick illustrated in Fig. 37 shows how seven degrees of freedom can be controlled with a single joystick, although it is unusual to make joysticks so complex.

Table 12—Comparison of Force-Operated and Position-Operated Teleoperator Controls*

Force-Operated (Isometric)	Position-Operated (Isotonic)
Controller output corresponds to forces applied by operator; "natural" control	Controller output does not correspond to forces applied by operator; an interpretive step is required for control
Controller output drops to zero unless manual force is maintained on the controller; i.e., it is self-centering	Control lever remains at position last set; output remains applied without maintaining manual force. (Controller usually maintains a set position by virtue of sliding friction.)
A large output range may be accurately controlled by a small range of control lever displacement	To control a large output range accurately, a large range of control lever movement is needed
Large manual forces are required to control a large output range accurately	A large output range can be controlled accurately with very small manual forces
Because large manual forces are required to control a large output range accurately, a controller must be built and located so the operator may exert large manual forces on it	Because a large output range can be controlled accurately with very small manual forces, many types of controls, in a large range of locations, may be employed.

*Adapted from Ref. 27.

Joysticks may be either force-operated *(isometric* or *"stiff-stick")* or position-operated *(isotonic)*. Manipulators have been constructed using both types. No clearcut advantages have been demonstrated for one over the other. Kelley has tabulated the relative advantages and disadvantages of the two types (Table 12).

A joystick is often a better control device than an array of switches because the operator identifies better with the task, particularly if the joystick is built along anthropomorphic lines like that pictured in Fig. 37. Crawford and Kama have compared operator performance on a unilateral rate-controlled manipulator using both a joystick and an array of levers.[60] They found the joystick to be superior. Pesch has compared the joystick against a pushbutton array and also found it superior.[61] The fact that several joints can be controlled by a single, rather anthropomorphic joystick also helps make this controller superior to switches and switchboxes.

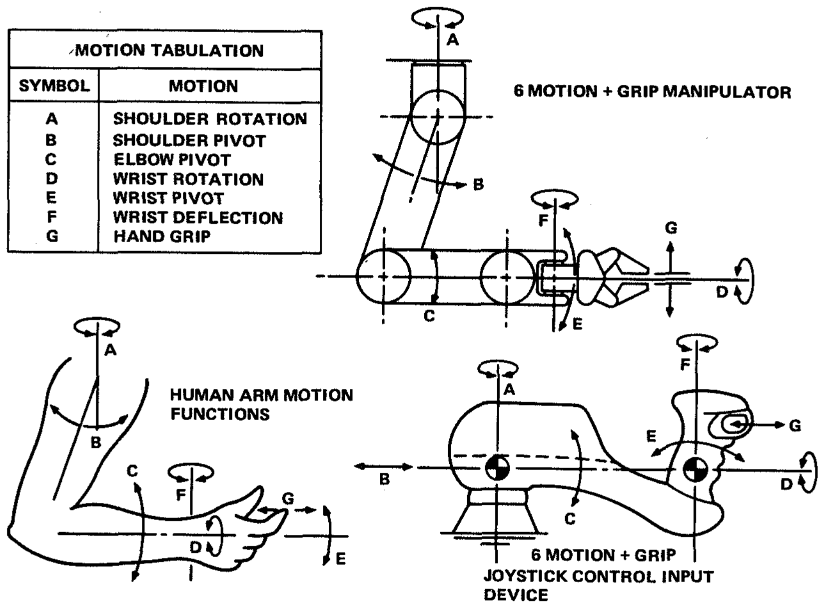

Figure 37 *Three drawings showing some parallelisms between operator arm, manipulator actuators, and a rather sophisticated joystick. Most joystick-controlled manipulators are unilateral despite the anthropomorphism shown here.*

The motions or pressures on a joystick activate the switches and (more commonly) potentiometers which control the joint motors. There is no force feedback in the usual joystick, although one can see how the addition of servos to the joystick might be accomplished.

Almost all unilateral manipulators now in operation employ switchbox controllers. But a few exceptions exist: one is the venerable General Mills 300 manipulator still in hot-cell use. Control of this unilateral manipulator is by two joysticks (Fig. 38). The General Mills control console is a rather formidable piece of equipment, but most joysticks can be made smaller and more portable. Westinghouse, for example, has constructed a small joystick for controlling the electrohydraulic manipulator arm it built for the Deep Sea Rescue Vehicle (DSRV-1). The DSRV joystick has the feature of shifting from one degree of freedom to another in much the same way one shifts gears in an automobile. In the left-hand position, the operator twists the control one way or the other to activate the manipulator shoulder joint; in the right-hand position control shifts to the elbow pivot; the forward position takes care of the wrist pivot. The back position, however, activates a supervisory control subroutine called True Arm Extension; a straight in-and-out motion for scrubbing, sawing, etc. Another rather sophisticated joystick built by Electric Boat is illustrated in Fig. 39.

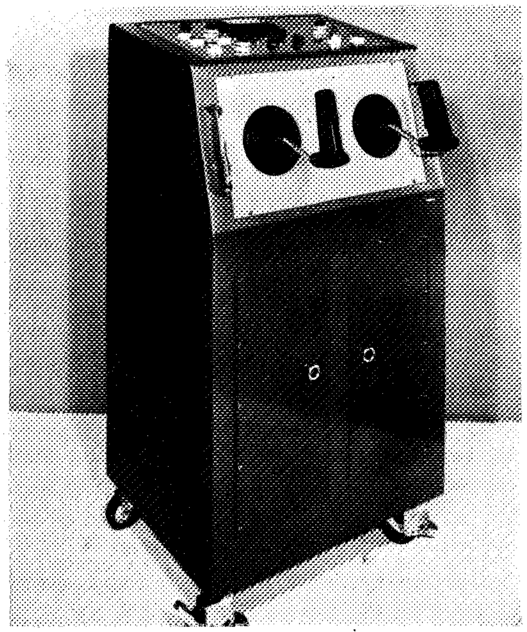

Figure 38 *The console and two joysticks employed in controlling the General Mills Model 300 electric unilateral manipulator. The left-hand joystick controls the overhead bridge carriage and hoist that positions the arm. The right-hand joystick controls all arm and hand motions. (Courtesy of R. Karinen, Programmed and Remote Systems.)*

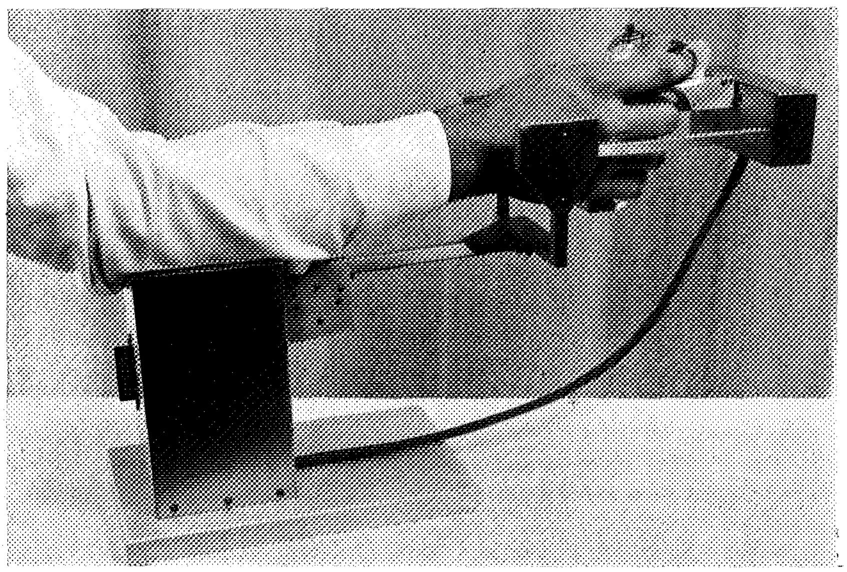

Figure 39 *A joystick-type control for an underseas electrohydraulic unilateral manipulator. (Courtesy of Electric Boat Division, General Dynamics.)*

Despite the potentialities of joystick control in the teleoperator field, joysticks are still used sparingly. Switches still predominate in the control of unilateral manipulators and, for that matter, artificial limbs.

ANALOG CONTROLS

Rather than push buttons or tilt joysticks to maneuver a manipulator arm into the desired position, why not make the controller an analog or replica of the working arm and design controls that force the working arm to duplicate the configuration of the control?* This, of course, is approximately what a master-slave manipulator does. Master-slaves are a step more complicated, though, because they also provide force feedback. The usual analog control displays no force feedback, although it could be built in as in the case of the joystick. In fact, an analog control can be thought of as a many-jointed joystick, although it is neither isotonic nor isometric.

Each joint in the analog control master arm has a potentiometer pickoff which supplies a signal to the real arm. If the slave arm is in a configuration different from that of the control arm, the corresponding signals from pickoffs on the slave arm will not correspond to those from the master control arm. Joint motors will be driven until all differences are nulled and master and slave arm configurations are identical.† The word "configuration" is used here intentionally because configurations but not linear motions are identical—even if the control arm is considerably smaller than the actual arm (a useful feature aboard a crowded submersible). During manipulator operation, an arm activated by an analog control may lag significantly behind the motion of the master control because joint motors have limited speeds. Thus, there is not necessarily good spatial correspondence.

The advantages of analog control are several:

1. The controls can be made much smaller (or larger) than the slave arm/hand combination.
2. The controls can be activated from the master-hand area alone, with the rest of the joints following the hand motion naturally—like railroad cars. Some arms, such as those of Project MAC, are made with many more joints than the human arm to facilitate this sort of *terminus control.*
3. Force feedback can be accommodated easily.

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*This is called *analog control, replica control, model* (or *model-arm) control, position-servo control,* and, if the control arm is smaller than the real arm, *miniature-arm control.*

†The use of the words "master" and "slave" should not make the reader confuse analog-controlled manipulators with master-slaves; master-slaves can be actuated from the slave side (they are truly bilateral) but an analog-controlled unilateral manipulator cannot.

4. Preprogramming for supervisory control consists simply of providing simulated pickoff voltages. As an alternate, routine motions can be accurately carried out using a grooved template; with terminus control the grooves are in essence preprogrammed instructions. (Picture the operator holding the master terminus like a pencil and following the template grooves.)

There are some very real difficulties, too:

1. Cost and complexity.
2. It is difficult to incorporate physically all the necessary circuits and electrical components, particularly in miniature master control arms.
3. With a miniature analog control, small motions are greatly amplified in the slave arm.
4. Considerable friction or an automatic braking system has to be built into the analog control arm so that it (and the slave arm) will not collapse when the operator releases it. This friction may fatigue the operator.

Almost all of the organizations engaged in undersea manipulator development have experimented with miniature analog controls. Generally speaking, the experiments have shown that analog control is feasible but that the disadvantages just listed outweigh the positive features. Most undersea manipulators are still controlled by switchboxes and joysticks.

Programmed and Remote Systems (PaR) has developed an interesting joystick-like control for unilateral manipulators that has some resemblance to an analog control (Fig. 40). In the PaR Position Controller the control device is a rough model of the actual manipulator arm. Instead of position pickoffs, though, the control joints utilize rate pickoffs. Thus, as the controls are moved, signals proportional to speed of joint rotation drive the manipulator motors (via pulse-counting circuitry) at the same angular rate as the control joints. Spatial correspondence (*configuration correspondence* is more accurate) may not be maintained because the control arm can be moved faster than the drive motors can position the real arm. However, the rate-control circuits are activated only when the trigger on the Position Controller is pulled; controls can be repositioned to recapture configuration correspondence when necessary.

MASTER-SLAVE AND SIMILAR BILATERAL CONTROLS

The master-slave manipulator concept was pioneered by Argonne National Laboratory (ANL) in the late 1940s, when R. C. Goertz's group developed the first mechanical master-slaves. Later, ANL developed a series of electrical master-slaves. These machines are described in the first volume of this survey.[1] Master-slaves are bilateral teleoperators in which forces and

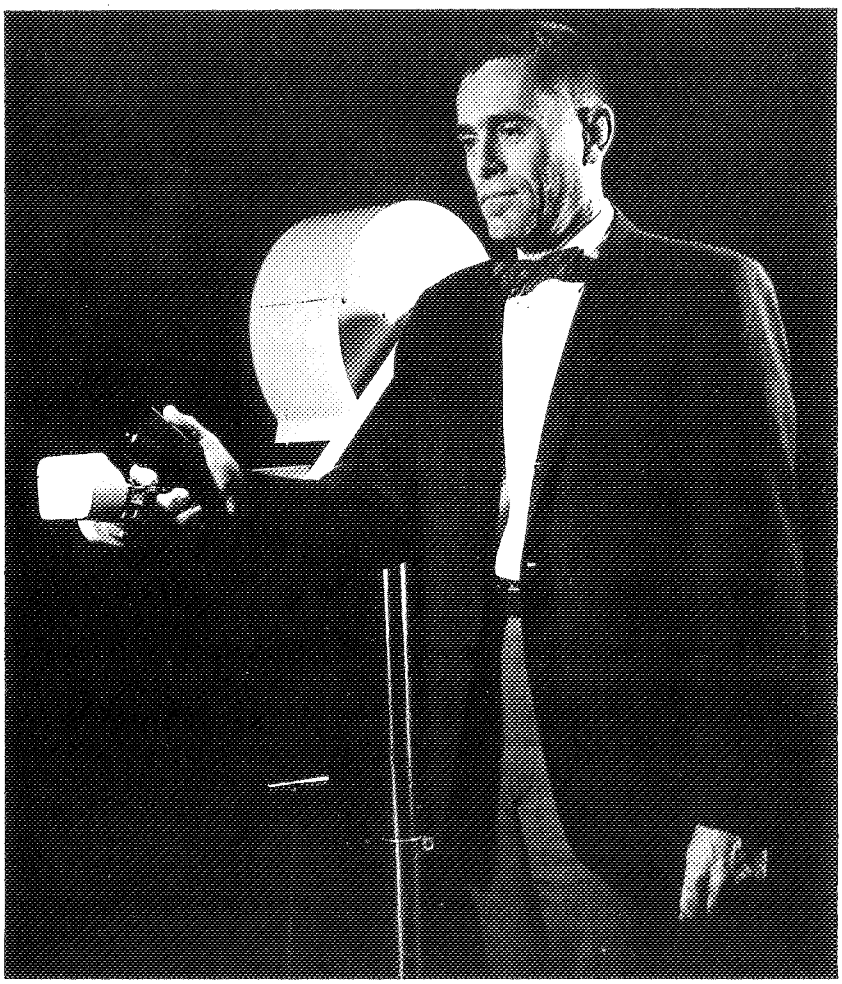


Figure 40 *The PaR Position Controller, a special joystick-type control for a unilateral manipulator. This type of control is more anthropomorphic than the usual switchbox controls. (Courtesy of R. Karinen, Programmed and Remote Systems.)*

torques at the master controls are proportionally reproduced at the slave actuators and vice versa. Normally, there are seven degrees of freedom, all of which can be controlled simultaneously (Fig. 6). Master-slave controls have fingers, shoulder, and wrist joints, which make them considerably more anthropomorphic than the switchboxes and joysticks just discussed. Operation of master-slaves is natural and the operator easily projects himself into the work area. Spatial correspondence also exists. The mechanical master-slaves, particularly the famous ANL-developed Mod-8, are relatively inexpensive, reliable, versatile, and easy-to-operate. They are among the most common teleoperators in operational use.

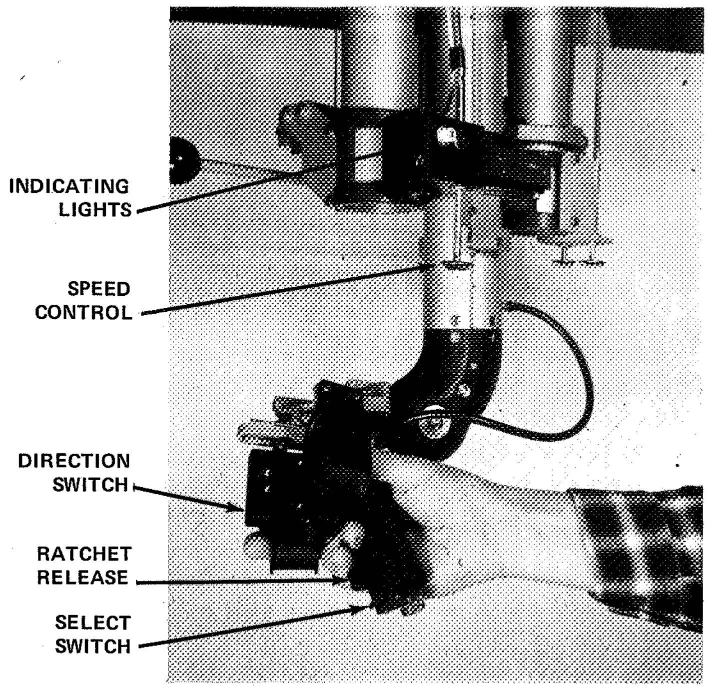
The seven degrees of freedom in the mechanical master-slaves are activated by mechanical linkages that physically tie the controls to the actuators. Many of the operator's motions, say, wrist action, are communicated via metal tapes or cables. In a sense, the mechanical master-slave is a rather complicated pantograph, with one-to-one spatial correspondence. It differs from the analog controls in the sense that it is completely mechanical and possesses force feedback.*

The master hands of the mechanical master-slaves are the focus of the operator's attention. When he wishes to pick up an object he moves the master hand to the object; both master and slave arms accommodate; this is much like the terminus control employed with analog controls. It is position control as opposed to the rate control employed in most switch and joystick-controlled unilateral manipulators. Once in the vicinity of the object, the operator makes fine position adjustments and orients the wrist. He then grasps the object with the fingers or tongs. Thus, master-slave manipulation actually consists of coarse terminus control followed by fine hand adjustments.

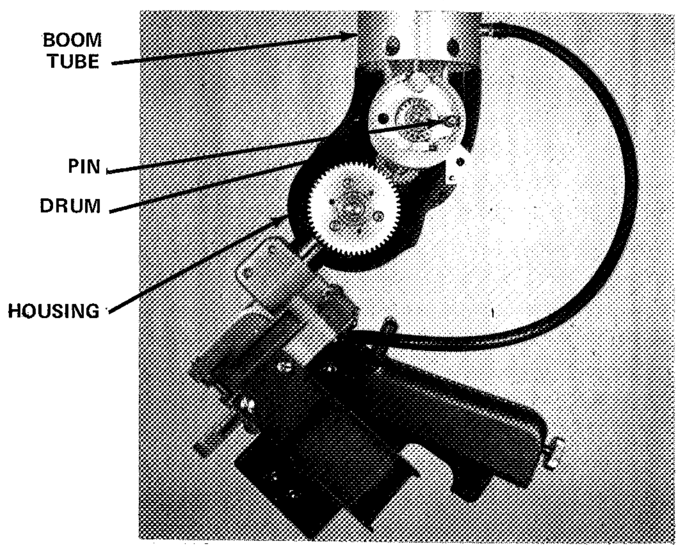
Master-slave hands are anthropomorphic in that the slave fingers are controlled by the human thumb and forefinger, the same digits we use to pick up objects in everyday life (Fig. 41). The wrist joint, too, is "natural." The typical master hand also possesses some joystick characteristics. The pistol grip is surrounded by switches, buttons, status lights, and levers that add versatility to the teleoperator. To illustrate, the manipulator may be locked in position so that the operator may leave his station without having master and slave collapse under the influence of gravity. Force amplification may be introduced between master and slave fingers. Even with these "unnatural" side benefits, master-slave controls represent a large step toward anthropomorphic controls.

The physical configurations of the ANL electrical master-slaves are patterned after their mechanical predecessors. The master hands, for example, are similar in both the mechanical and electrical species. The major difference between the two is that the metal tapes and cables connecting master to slave are replaced by servos and electrical signals. The electrical signals may move via hardwire or radio. It is this last fact that greatly increases the versatility of the electrical master-slave over its mechanical cousin. Master and slave stations can be hundreds of feet or millions of miles apart when one dispenses with mechanical linkages. Electrical master-slaves therefore can be considered for use in outer space or wherever great distance separates master and slave stations. Moreover, penetrations in hard-to-seal barriers, such as spaceship or

*Of course, analog controls are electrical and often miniaturized; but they could be mechanical in principle.



(a)



(b)

Figure 41 *Master hand of a Central Research Laboratories Mod-8 mechanical master-slave. (a) fully assembled hand, (b) hand dissembled, showing wrist gearing and tape drum. (Courtesy of Central Research Laboratories.)*

submersible hulls, are easier to design for electrical wires than moving tapes and cables. With the added versatility of the electric master-slaves came increased cost and complexity. Because of these factors, electrical master-slaves have not yet been widely used.

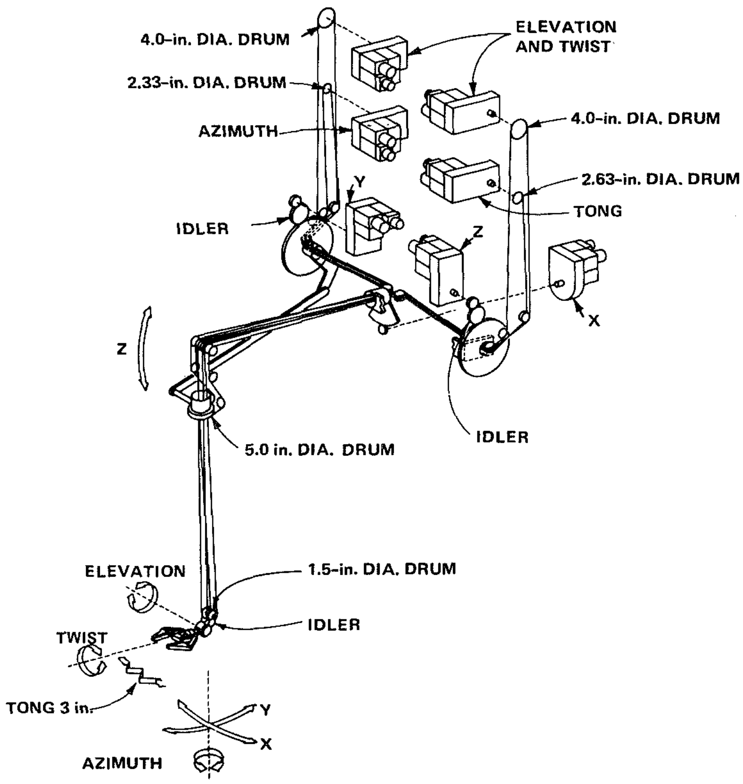


Figure 42 *The ANL Mark E4A slave-arm schematic. The master-arm displays a similar configuration.*[62]

In the ANL electrical master-slaves, the operator's input motions are first communicated to rotary drums with position sensors by means of metal-tape linkages. Thus, the master controls are similar to the mechanical master slaves up to the drums (Fig. 42). On the slave side, the situation is reversed; servo motors drive drums and metal tapes that actuate the corresponding degrees of freedom. Each of the seven degrees of freedom requires a master servo drive unit with two, 60-cycle, low inertia servo motors (Fig. 43). As in all true master-slaves, the slave hand and arm can control the master—the real meaning of bilateralness. On the slave side, four servos are used. Geared synchromotors on each side provide positional information. The servo system block diagram for the ANL Mark E4A is presented in Fig. 44.

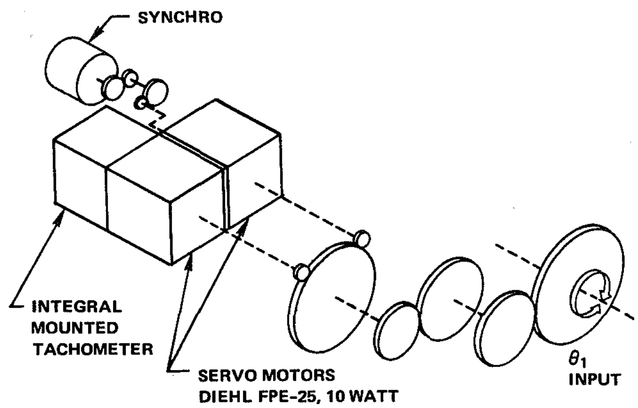


Figure 43 *ANL E4A master servo drive unit.*[62]

During 1966 and 1967, ANL participated with NASA's Marshall Space Flight Center and their contractor, Ling-Temco-Vought, in a study of manipulators for use in orbital spacecraft.[63] One of the spacecraft studied was the Space Taxi, illustrated in Fig. 45 with two electrical master-slave working arms and three less sophisticated docking arms. In this study, ANL proposed mechanical master-slaves for early availability and electrical master-slaves as the best solution, given adequate development time.

One of the basic control problems encountered in this study was the operator's limited working volume, a situation reminiscent of that on small submersibles, where switchboxes and joysticks are the common solutions. The ANL-recommended teleoperator configuration inverted the usual master-slave arrangement. The working arms are mounted at the spacecraft bottom, below the operator's feet, giving him an unobstructed view and freeing cabin volume for torso and arm movements. Instead of the usual master hand control (Fig. 41), a master handle or joystick with a trigger and switches was proposed (Fig. 46). The master handle (the analog of the slave hand) would be position-controlled, just as in the normal terrestrial master-slave. There is a strong resemblance between this control handle, the PaR Position Controller (Fig. 40) and the Electric Boat joystick (Fig. 39). The ANL approach, of course, offers force feedback—a valuable commodity in manipulation—which the others do not.

The problem of restricted operator volume (Fig. 46) was solved in the ANL study by the use of indexing. Indexing involves driving the slave arm independently of the master. If the operator cannot reach something because he has reached the limit of movement of the master control, he can gain additional slave arm motion through the use of indexing motors. As the slave moves, the master can be repositioned. The effective working volume of a bilateral master-slave can thus be increased by unilateral, switch-controlled

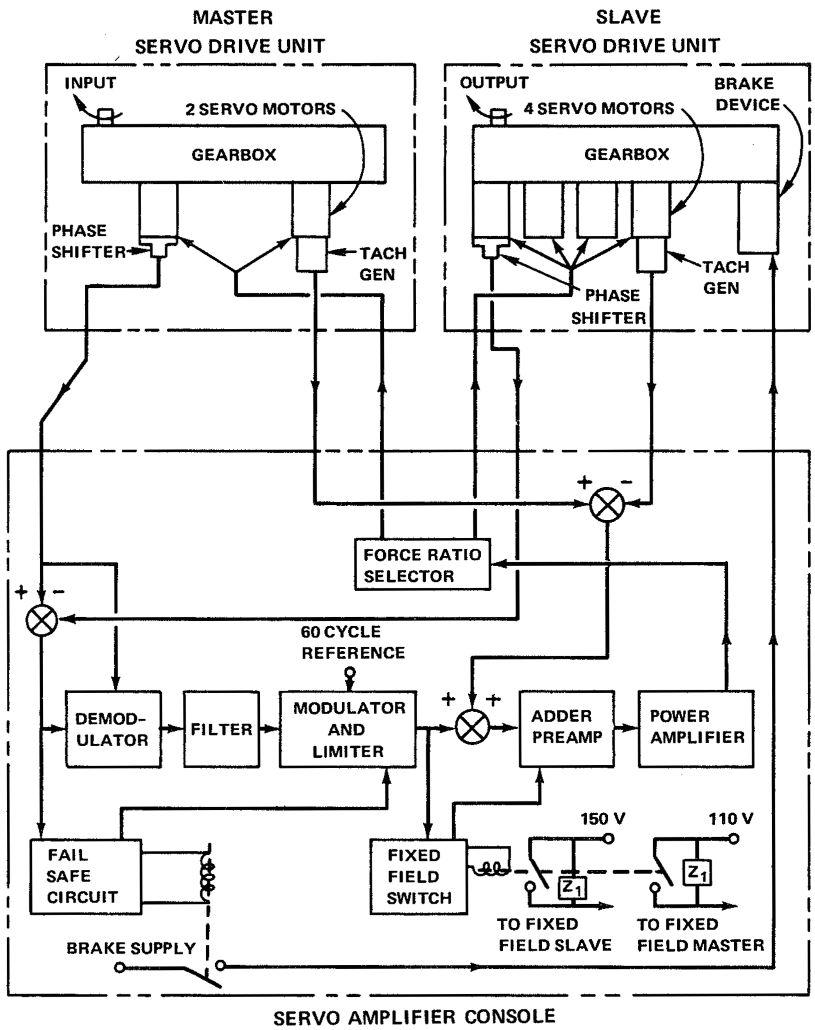


Figure 44 *Servo block diagram for the ANL E4A electrical master-slave (one degree of freedom only).*[62]

motors. The indexing control switches are often located on the master hands in master-slaves. Obviously, there is some loss of spatial correspondence when indexing is employed—the price of expanding operating volume.

Automatic indexing appeared promising in the ANL space study. Whenever the master hand would reach the bounds of the operating envelope, index motors would automatically switch on until the master hand was operating again in the prescribed volume (Fig. 47). In practice, an override or initiate switch could be installed on the master handle to give the operator

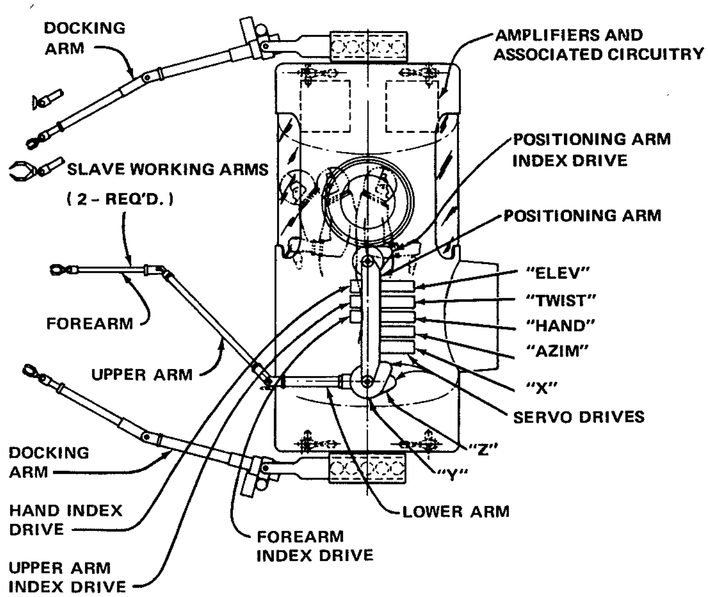


Figure 45 *The ANL-LTV-MSFC Space Taxi master-slave electric manipulator arrangement. There are two master-slave working arms and three docking arms.*[63]

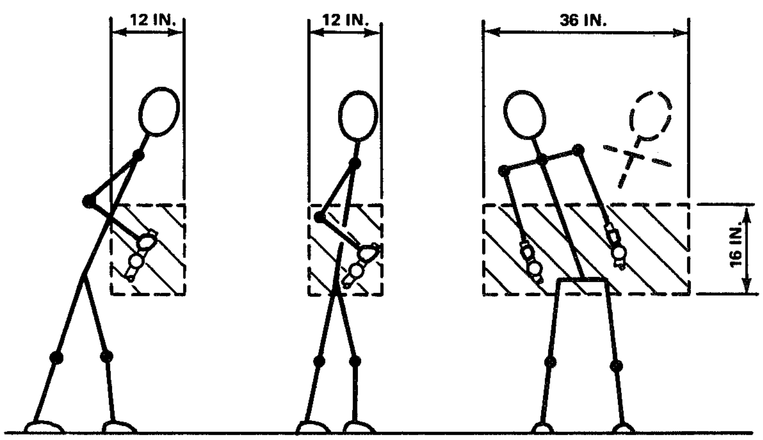


Figure 46 *The minimum indexing volume assumed in the ANL-LTV-MSFC space manipulator study; dimensions are in inches.*[63]

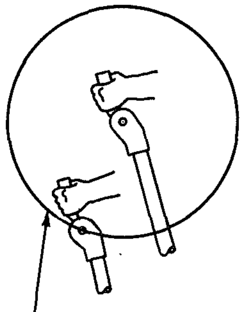


Figure 47 *In the ANL-proposed approach to orbital manipulation, automatic indexing commences when the master handle reaches the outer bounds of a previously established control volume.*[63]

control over the otherwise automatic indexing motions. ANL studies indicated that the "permissive" initiate switch provided somewhat better control.[63]

Several other electrical bilateral manipulators have been built. One of the most sophisticated and most interesting was the Handyman electrohydraulic bilateral manipulator built by General Electric for the Aircraft Nuclear Propulsion program in the 1950s.* Handyman, with ten servoed joints in each arm-hand combination, was better articulated than the ANL seven-degree-of-freedom master-slave. Another departure from the basic ANL master-slave configuration was the more faithful paralleling of human joints with control joints. As shown in Fig. 48, the Handyman master controls are almost exoskeletal, particularly the forearms and hands. Even the hand is articulated. In other words, Handyman takes a further step toward anthropomorphism. One of the rewards is greater dexterity and more compliance with human manipulatory tasks. In fact, one of Handyman's stocks in trade was its ability to twirl hula hoops, something difficult for the standard master-slave configuration and next to impossible for unilateral manipulators. Along with more joints and greater dexterity went complexity and attendant loss of reliability and increased cost. Handyman never saw much operational use, but it does stand as a milestone in teleoperator development.

Handyman was made bilateral by joining in one loop a pair of position-error servos, connecting them in tandem so that their error signals are made common.[64] This common error signal provided a means for reflecting force back to the operator (Fig. 49). Figure 50 illustrates the Handyman servo loops for one degree of freedom in more detail. There were four separate loops; the upper provided position feedback, the two center

*For more complete descriptions of these teleoperator systems, see Ref. 1.

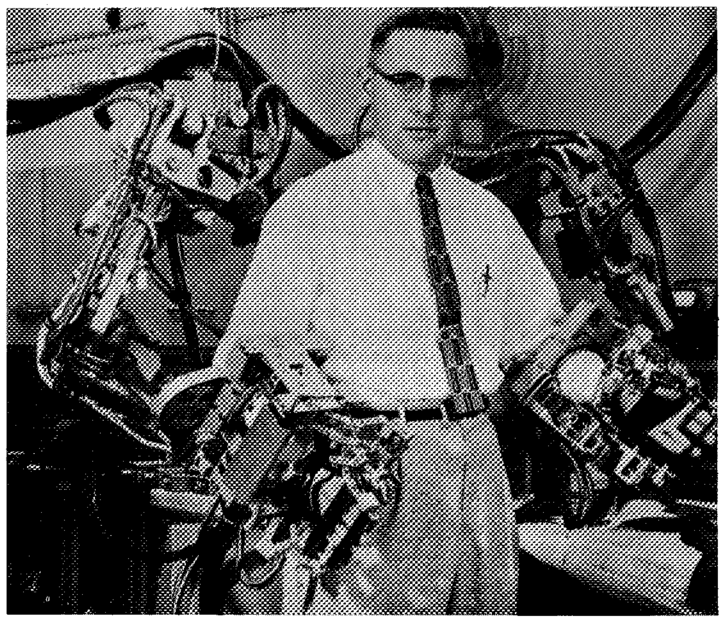


Figure 48 *The Handyman master station. There are ten bilateral servo loops in each arm-hand combination. Note the exoskeletal aspects, particularly around the forearm and hand. (Courtesy of R. S. Mosher, General Electric Co.)*

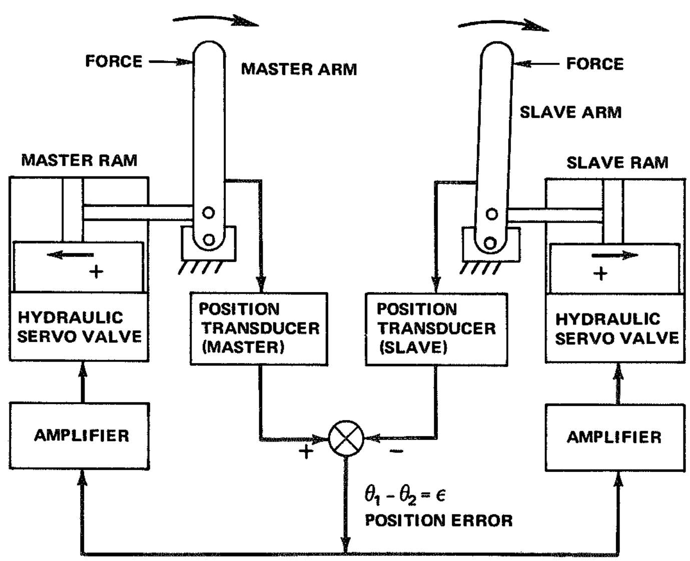


Figure 49 *Servo block diagram for the Handyman electrohydraulic manipulator built by General Electric.*[64]

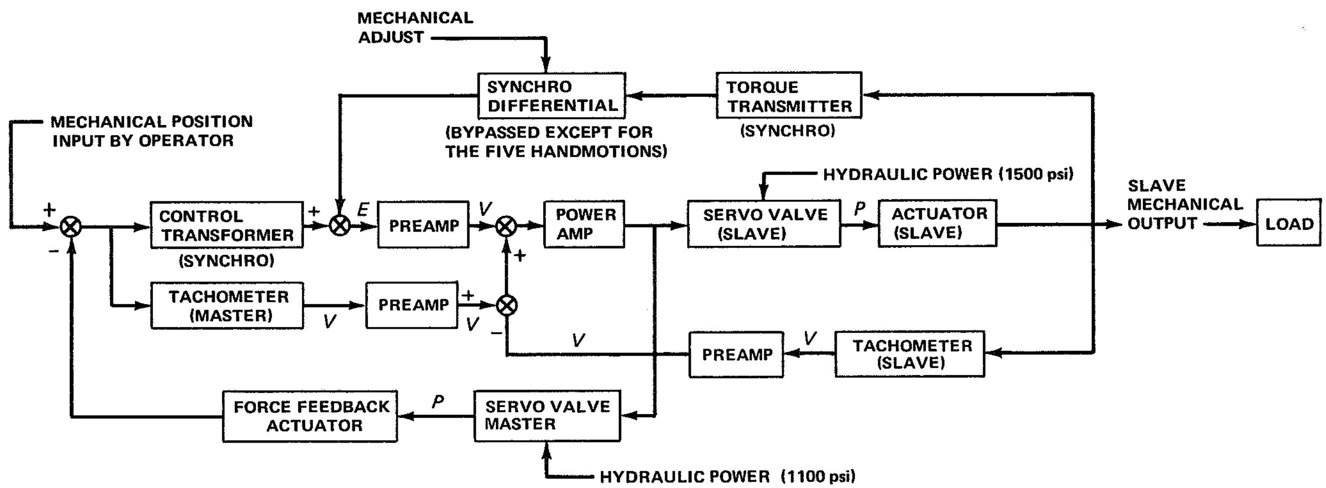


Figure 50 *The servo loops for one degree of freedom in the Handyman bilateral electrohydraulic manipulator.*[64]

measured and compared velocities, and the lower loop provided force feedback.

As the operator generated a position input, his action was opposed by the force feedback from the lower loop. If a force greater than the feedback was exerted, the resultant mechanical motion was converted into an electrical signal by the control transformer. This signal was added to the position signal arriving at the summing point from the upper loop. The two signals then entered the preamplifier. Introduced at the next summing point was a velocity signal resulting from the comparison of master and slave tachometers. This signal introduced damping if the slave actuator began to move too rapidly. The power amplifier next received the signals from the summing point. It combined and amplified them, then it transmitted the result into the lower feedback loop and the slave servo valve. The servo valve motion caused the slave joint to move.

A potential source of instability in Handyman was the mutual interaction between the joints and servo systems. Critical damping prevented this. General Electric encountered a similar problem with the Hardiman man amplifier (see Chap. 3).

At the AEC's Brookhaven National Laboratory (BNL) another electrical bilateral manipulator has been developed for use with high energy accelerators.[65] The BNL approach differs from that used by ANL in the application of D.C. servos at the joints themselves instead of at the top of the manipulator connected by tapes and cables to the joints. Flatau has claimed the following direct advantages:

1. Better frequency response due to direct coupling of motions.
2. Complete articulation of all motions, such as continuous rotation of the slave joints due to the absence of interconnecting cables.
3. Simplification due to the absence of metal tapes and cables.

Naturally, there are disadvantages, too:

1. Inability to use identical servo packages for all joints.
2. Arms are heavy due to servo equipment installed therein.
3. Somewhat large brush and hysteresis friction in compact D.C. torque motors.

The final bilateral teleoperator considered here is the all-hydraulic Hydroman, developed at Oak Ridge National Laboratory for manipulating heavy loads in hot cells.[66] Hydroman's hydraulic control circuit is portrayed in Fig. 51. This manipulator possesses force feedback and employs a joystick-like control hand.

Summarizing, the bilateral master-slaves and other associated bilateral manipulators add the dimension of force feedback to manipulation. Except in the case of the simple and ubiquitous mechanical master-slaves, the cost of mechanizing force feedback in terms of money, complexity, and reliability

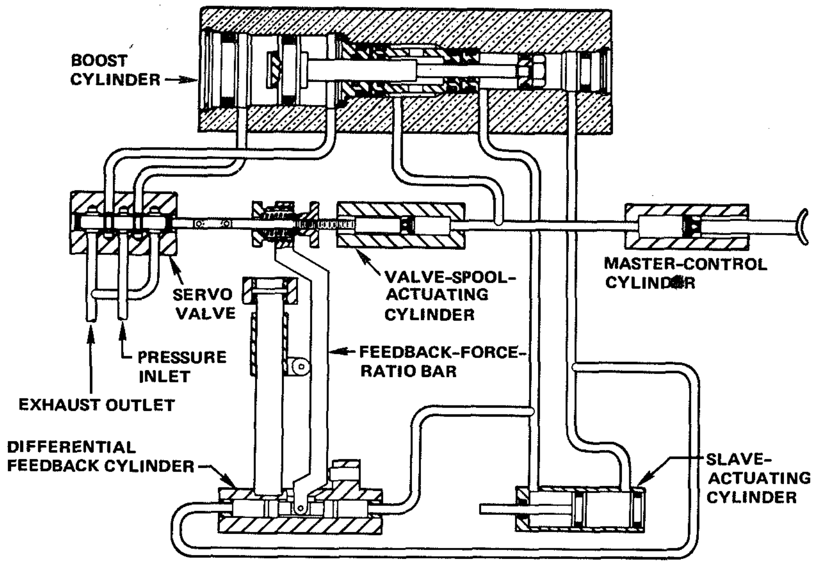


Figure 51 *The hydraulic control schematic for the Oak Ridge Hydroman heavy-duty manipulator.*[66]

has militated against widespread application. The ANL electrical master-slaves have proven highly versatile and effective in hot-cell work, but still they have not been adopted for underseas work—a most logical application from many standpoints. When manipulation at great distance is contemplated, as in the space program, there is no alternative to electrical master-slaves if force feedback is considered essential. However, even here there is a catch: the greater the distance separating the master and slave stations, the greater the time delay in force feedback. While electrical master-slaves may be useful in orbital work, they may be far less attractive on the Moon because an Earth-based operator will not feel the reaction forces for over one second. However, teleoperators controlled from a manned lunar lander would be very useful in reconnoitering the Moon; time delay would be negligible here.

WALKING MACHINE CONTROL

If good hand-arm teleoperators can be manufactured, why not leg-foot teleoperators; that is, a walking machine, a pedipulator rather than a manipulator? Walking machines can be made with ease; a great many of them have been constructed over the ages, from small walking toys to huge drag-line machines used in mining work. All of these machines have one thing in common; they are preprogrammed. Being preprogrammed they are completely deterministic, treading ahead blindly regardless of the terrain or obstacles. Even the more modern and sophisticated experimental walking machines built by Shigley and Space/General (see Ref. 1) permit the operator to do no more than start, stop, and steer. For good off-road mobility, however, we need either a highly adaptive, operator-less control system or a human operator to provide the adaptation to terrain and obstacles in person.

In Chapter 3, we mentioned the digital, adaptive control scheme suggested by Hoch, at Battelle–Northwest Laboratories. In this scheme, adaptation to terrain is accomplished by the analysis of feedback signals from the joints of the walking machine. Because the operator would merely drive the propelled vehicle, the machine would not be a teleoperator as defined in this book. To qualify as a teleoperator, a walking machine must have man in the control loop, although he might initiate certain walking subroutines, particularly on easy, relatively flat terrain and when operating on prepared surfaces.

If man is to be an intimate part of the control loop, the first impulse is to build the walking machine like man; that is, a biped. Instead of controlling teleoperator arms, man would control legs. R. S. Mosher, at General Electric, has suggested such two-legged pedipulators. General Electric is now developing a man amplifier under DOD sponsorship which is essentially an exoskeletal biped walking machine with servoed arms. However, the purpose of this machine, which is called Hardiman, is man amplification, not off-road mobility, and we reserve discussion of this machine until the next section.

There seems little argument that a biped pedipulator would work if carefully controlled by man. General Electric has actually built a Pedipulator Balance Demonstrator that has proven that man can balance himself easily atop a two-legged servoed machine.[67] In operating this balancing machine, the operator's head is some fifteen feet from the floor and there is a natural fear of falling. Nevertheless, operators quickly learn to rely on their senses of balance and control the machine successfully. From the neuromuscular standpoint, a neophyte operator "knows" how to operate the machine immediately—the GE balance machine is that anthropomorphic.

Despite the success of the Pedipulator Balance Demonstrator, Bradley and others have pointed out that a biped walking machine can still fall, just as a man does on occasion, then the machine would be out of commission until a crane came along to right it.[68] For this and several other reasons not associated with control, development interest has now focused on quadruped walking machines. In this kind of teleoperator, the human operator controls one pair of legs with his legs and the other set with his arms—more or less as if he were crawling. Objections to the four-footed walking machine concept have been raised by engineers at the Army's Rock Island Arsenal.[69] Briefly, this critique asserts that walking stability in a quadruped is a strong function of its active torso. For example, no gait can be found that does not call for lifting a leg on a heavy corner; unless the animal's torso helps shift the center of gravity there will be a fall. Since the quadruped walking machine does not

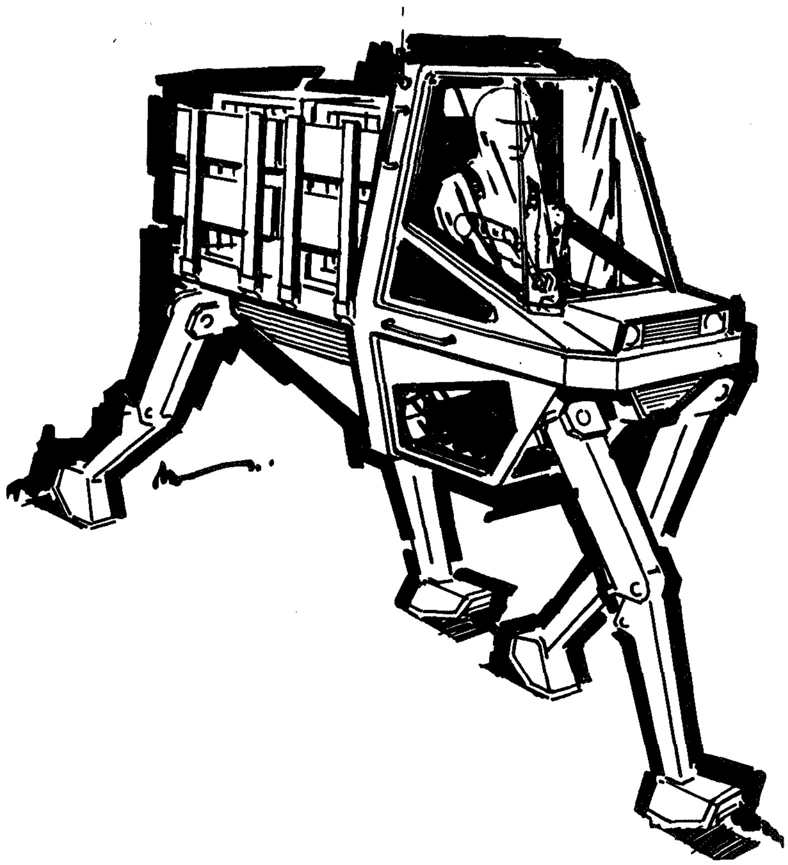


Figure 52 *Artist's concept of the Walking Truck. (Courtesy of General Electric Co.)*

possess a controlled, articulated torso or other means of shifting balance, this critique claims that instability is likely. The Rock Island Arsenal report concludes that hexapeds or octapeds—controlled automatically—would be more reasonable engineering solutions to off-road mobility.

The quadruped concept is being tested in a General Electric development program sponsored jointly by the Army Tank-Automotive Command and the Advanced Research Projects Agency. The objectives of the Walking Truck or Quadruped program are to design, construct, and test a full-scale, four-legged walking machine capable of carrying an operator and 500 pounds of cargo (Fig. 52). Each leg of the Walking Truck has three joints powered by force-reflecting hydraulic servos.

A major requirement in the Walking Truck program is the development of effective operator controls. A full-scale simulator was built to test out ideas

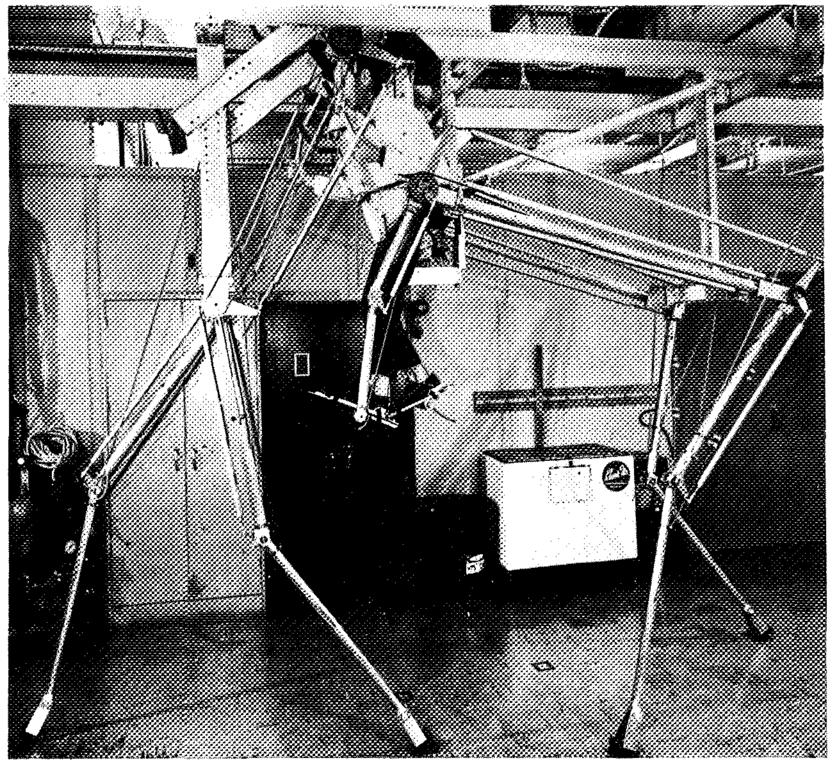


Figure 53 *A quadruped simulator. The simulator is mechanically linked to the operator's motions. (Courtesy of General Electric Co.)*

(Fig. 53). The simulator was unpowered but the controls were mechanically connected to the truck legs to provide force feedback and position spatial correspondence. During operation, the simulator was suspended by a crane, and the operator executed walking and turning maneuvers. Human factors analysis of simulator tests indicated that satisfactory control of all leg motions could be accomplished by a single operator. The simulator, of course, could not check out the assertion of the Rock Island Arsenal engineers that the machine would fall over in practice.

General Electric has constructed some prototype hardware for the Walking Truck (Fig. 54). The operator sits in a seat wearing exoskeletal controls around all four limbs (Fig. 55). A master control arm is illustrated in Fig. 56. Metal cables transmit control forces to hydraulic servo-valve actuators. Force is reflected hydraulically from each joint to the corresponding master joint where it is felt by the operator. There is exact kinematic symmetry between the master controls and the actual legs. The controls can

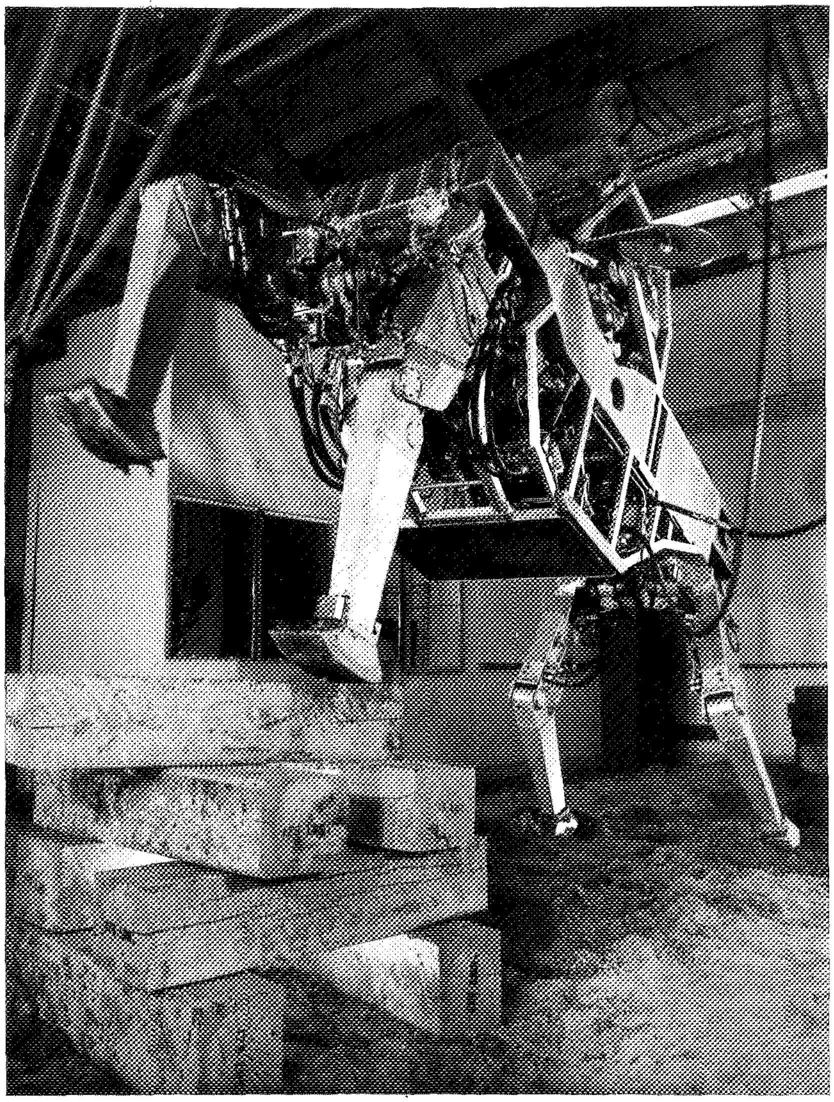


Figure 54 *Photograph of the Walking Truck prototype developed by GE for DOD. (Courtesy of General Electric Co.)*

be adjusted to fit different operators. In addition, the force levels required for control can be adjusted for best agility and least fatigue. The instability predicted by Rock Island Arsenal engineers has not been encountered in this design. The Walking Truck, a major advance in the teleoperator field, boasts twelve servoed, force-reflecting joints. It is an intimate combination of machine and man-as-a-whole.

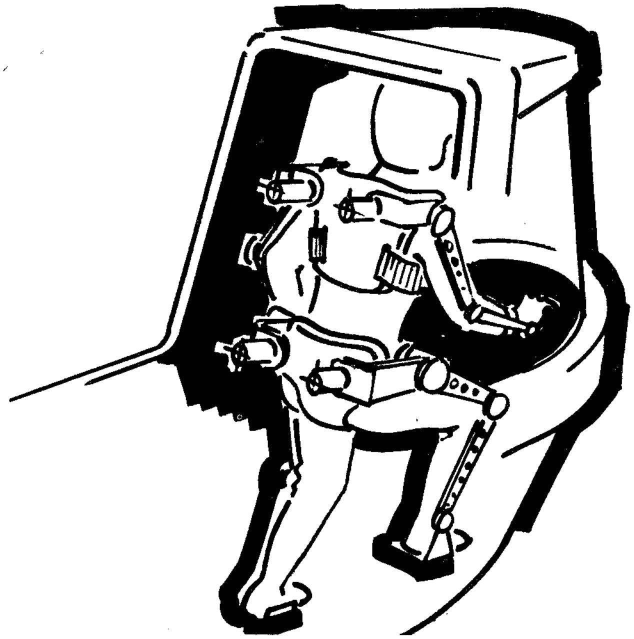


Figure 55 *The operator uses arms and legs to control the four-footed Walking Truck. (Courtesy of General Electric Co.)*

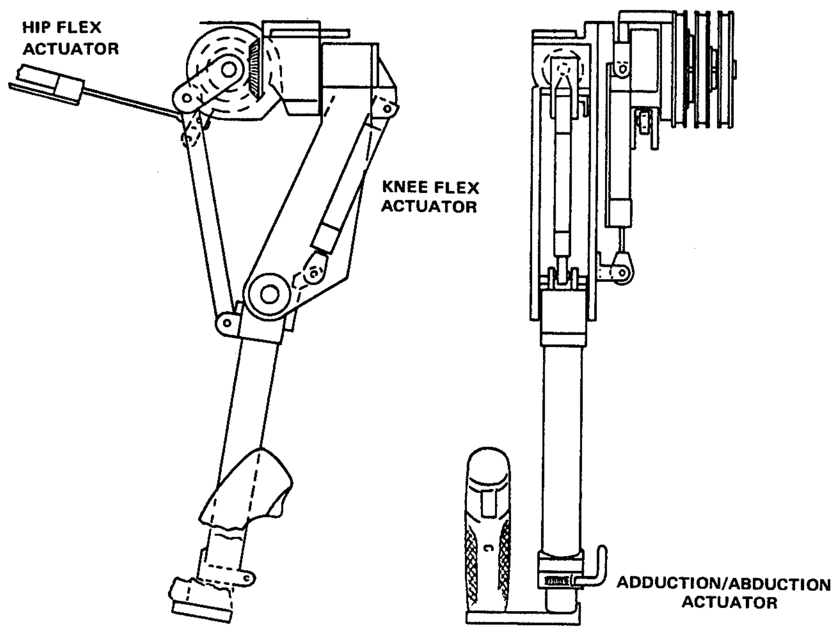


Figure 56 *Schematic drawing of a master control for a walking machine.*[70]

MAN-AMPLIFIER CONTROL

A man amplifier is an exoskeletal teleoperator that greatly increases the physical strength of the operator wearing the structure. The artist's concept of the General Electric Hardiman readily shows the marriage of the Walking Truck legs (Fig. 55) with the Handyman arms (Fig. 48). The result is a machine envelope for man, with many but not nearly all of man's articulations copied with bilateral servos. The design and applications of man amplifiers are discussed in more detail in Ref. 1.

Although Cornell Aeronautical Laboratory did considerable exploratory work on man amplifiers in the early 1960s,[71] the more recent General Electric Hardiman project* is the only effort that has attacked the hardware problems in depth.[70,72] Hardiman, with fifteen degrees of freedom (some in series), is considerably more complicated than even the Walking Truck. The project should be classified as "exploratory hardware development."

In the Hardiman concept, the operator stands inside an anthropomorphic structure built in two halves that are joined together only at the hips by a transverse member called the "girdle." The exoskeleton parallels the operator everywhere save at the forearms, where the exoskeleton completely surrounds the operator, and his arms are colinear rather than parallel with the exoskeleton forearms. This forearm arrangement simplifies controls and makes it easier for the operator to identify his arm with the slave arm. The slave hand consists of one servoed degree of freedom that forces an opposed "thumb" toward a V-shaped palm-finger structure. An additional thumb-tip joint is not servoed but responds to an operator on-off switch control.

The force ratio contemplated between master and slave structures is about 25. This immediately raises a question of operator safety should the slave exoskeleton somehow run amok. In the GE design, limbs are physically linked in such a way that small master-slave errors cannot build up to do damage. Another safety feature locks all actuators should hydraulic pressures or control signals fail. Collapse of a heavy exoskeleton—carrying perhaps a 2,000-pound load—would be very hazardous without such a provision.

The articulation and dimensions of the GE man-amplifier were determined by a study of the motions that it could perform and the range of individual operators that it could accommodate without major adjustments. Operators were assumed to range from the 10th to the 90th percentile in physical size. Ultimately, the degrees of freedom and dimensions illustrated in Fig. 57 were selected for each side of the master-slave. With 15 joints on each side, a man-amplifier could carry out most of the important human motions, save for those requiring considerable dexterity of the hand.

In the original Hardiman concept, the operator exerted a force against the closely fitting control surface at any particular degree of freedom. The

*The Hardiman project is sponsored jointly by the Army and Navy.

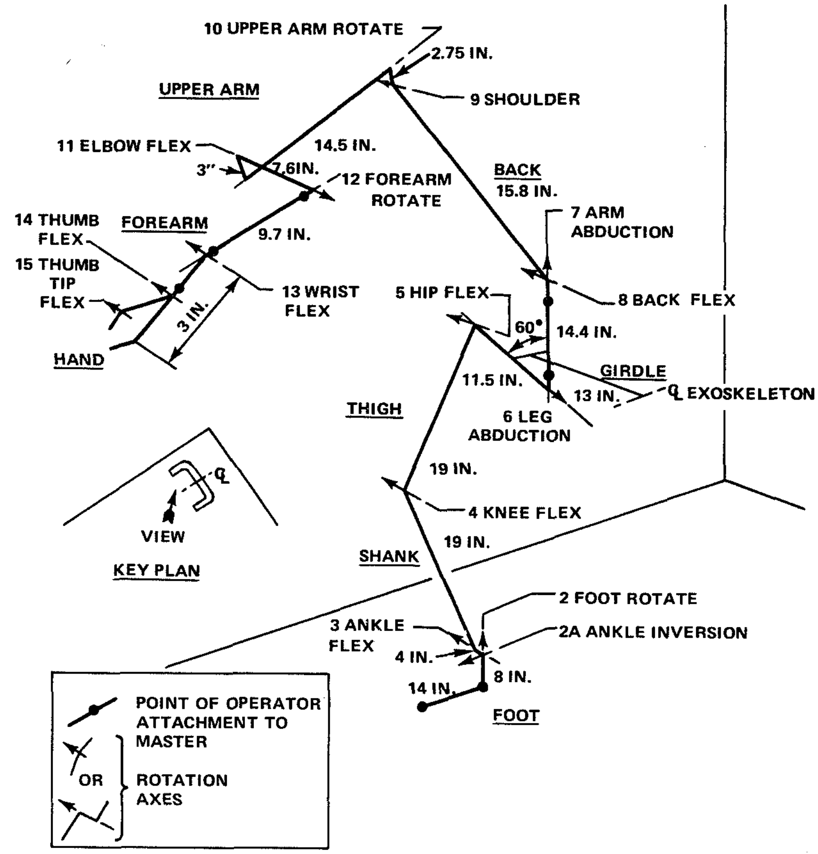


Figure 57 *Isometric stick figure showing the kinematic design of one half of the Hardiman exoskeleton. There are 15 degrees of freedom.*[70]

surface then moved relative to the encasing slave member and, in doing so, actuated a valve in the master control circuit. Several schemes were proposed for translating the operator movements into signals that would actuate the hydraulically powered slave joints. One was a simple "tickler" or finger connected directly to the hydraulic valve (Figs. 58 and 59). Tickler control was found to be unsatisfactory for the man-amplifier legs; and control of the joint angles was proposed for some leg degrees of freedom (Fig. 60).

By early 1968 the mechanical design of Hardiman-I had progressed to the point where it was evident that a machine housing a human controller could be built that could lift and manipulate 1500 pounds. Mechanical-hydraulic bilateral servo development, however, had not progressed as rapidly as General Electric had expected. The key development problem concerned the stabilization of three or more servoed joints in series. (See Chap. 3 for theory.) The Walking Truck and Handyman programs had proven that servo

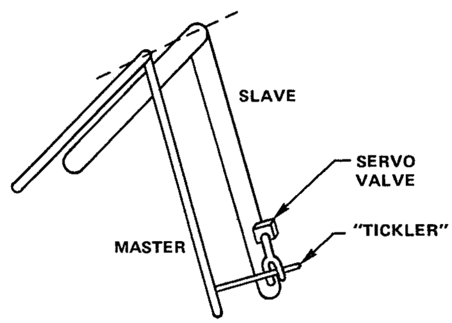


Figure 58 *Tickler control scheme linking master and slave in exoskeleton.*[70]

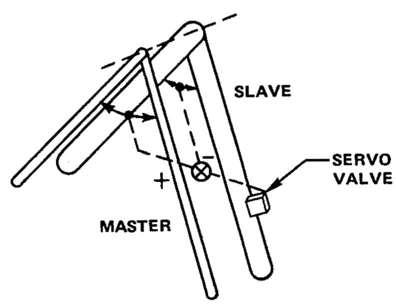


Figure 59 *Master and slave arrangement in angle control of joints.*[70]

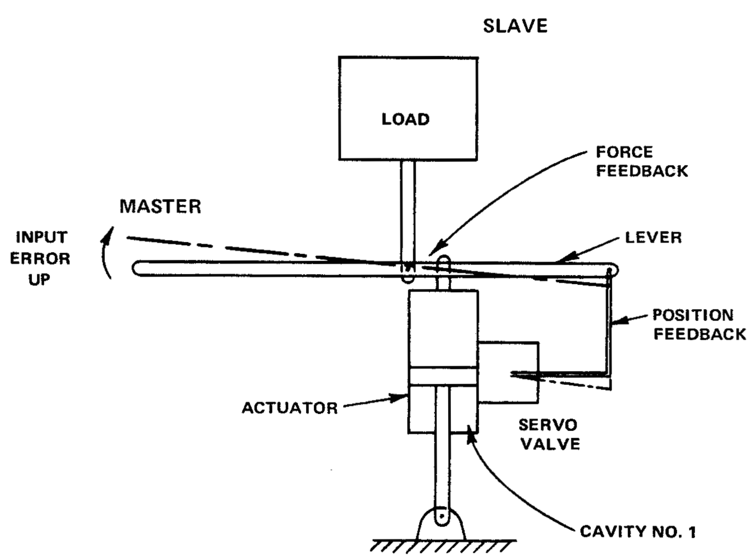


Figure 60 *Schematic of an exoskeleton servo linkage.*[70]

cascading was possible to a degree. But the Hardiman control requirements were so much more demanding that instability was likely using mechanical-hydraulic servos. General Electric, therefore, recommended replacing some mechanical-hydraulic servos with electrical-hydraulic servos because the latter can be stabilized rather easily using electrical circuits.[70]* Hardiman design is now proceeding on the basis of this change.

EYE SWITCHES AND OCULOMETERS

Although teleoperators are primarily manipulatory machines and normally should be controlled with the corresponding human extremities, there is no *a priori* barrier to the use of other parts of the operator's body for special control tasks. Man has no prehensile trunk or tail, but his eyes are remarkably well-controlled and, as we shall see shortly, his voice can be rich in symbolic commands.

It is difficult to mechanically harness the eye and derive control information from its motion. Optical pick-offs, however, have been developed for switching, gun aiming, and other purposes. Just how much of this technology is applicable to the teleoperator field?

NASA has developed an eye switch (Fig. 61) that depends upon the marked difference between the infrared reflection coefficient of the iris and

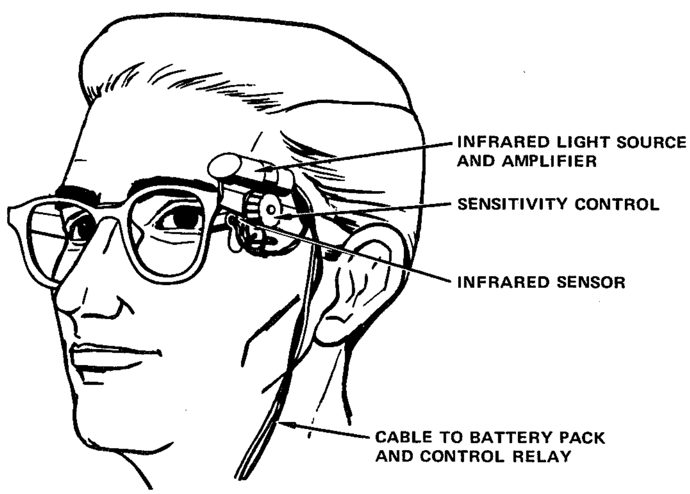


Figure 61 *Eyeball-controlled electrical switch. As the eye is voluntarily moved in the direction of the infrared sensor and light source, the eye's higher infrared reflectivity increases the sensor output sharply. (Adapted from NASA Tech Brief 65-10079.)*

*This reference contains extensive descriptions and hardware drawings of the original Hardiman approach.

the area surrounding it. The wearer-operator can voluntarily switch equipment on and off by directing his eye toward the infrared light source. As his eye moves, the infrared sensor mounted on the glasses frame detects the change in reflectivity and a switch is thereby closed or opened. If an operator's hands, feet and digits are busy with other controls, an eye switch may prove useful, especially in close, demanding manipulation. Auxiliary switches of this type are generally actuated by the thumb or fingers in extant teleoperators (see the illustrations of joysticks and master control hands earlier in this chapter). It would be unusual for an operator's extremities to be entirely saturated with the control task, but an eye switch might be convenient if an operator could not turn his head to look at a switchbox.

Honeywell and other organizations have designed and built eye-controls (called oculometers) that permit continuous control of machines.[73] In the oculometer the eye is illuminated with collimated light that is reflected by the cornea. The position of this reflection, relative to the center of the pupil, is proportional to eye direction. To obtain a control signal, the pupil area of the eye is imaged into the photocathode of an image dissector tube (Fig. 62). The pupil-iris boundary and the corneal reflection are acquired and tracked. The eye-direction control signal can be computed by comparing the relative positions of the pupil and the corneal reflection.

The oculometer developed by Honeywell under NASA contract is telescopic in configuration; that is, the operator must look through a telescope at a target. A helmet-mounted oculometer, though, is quite feasible; a possible configuration is shown in Fig. 63. With a helmet-mounted model, the operator retains normal, naked-eye vision and is free to move his head. The output signal would be proportional to the angle between the operator's eye axis and the forward axis of his head.

The primary applications of oculometers are in visual search, tracking, and instrument pointing. Conceivably, oculometer signals could steer walking machines and perhaps point sensors in the operating space, say, a television camera. In the next chapter, we shall see how head controls (not oculometers) have been employed to visually immobilize a TV scene in remote operations. An oculometer could also control TV cameras so that the operator sees on his TV monitor what his eyes would see if he were located in the working area.* Oculometers may also be combined with computer control of teleoperators. Man is an excellent identifier of objects and analyzer of situations existing in the working environment; the operator might merely look at a desired object and give the computer a signal to pick it up or perform some other operation on it. In other words, the oculometer can pinpoint the direction of a target for the teleoperator. Of course, intense

*Both the head and the eyes are used to select the scene viewed by the human eyes. Any eye-control system must distinguish between these two motions, say, by immobilizing the head.

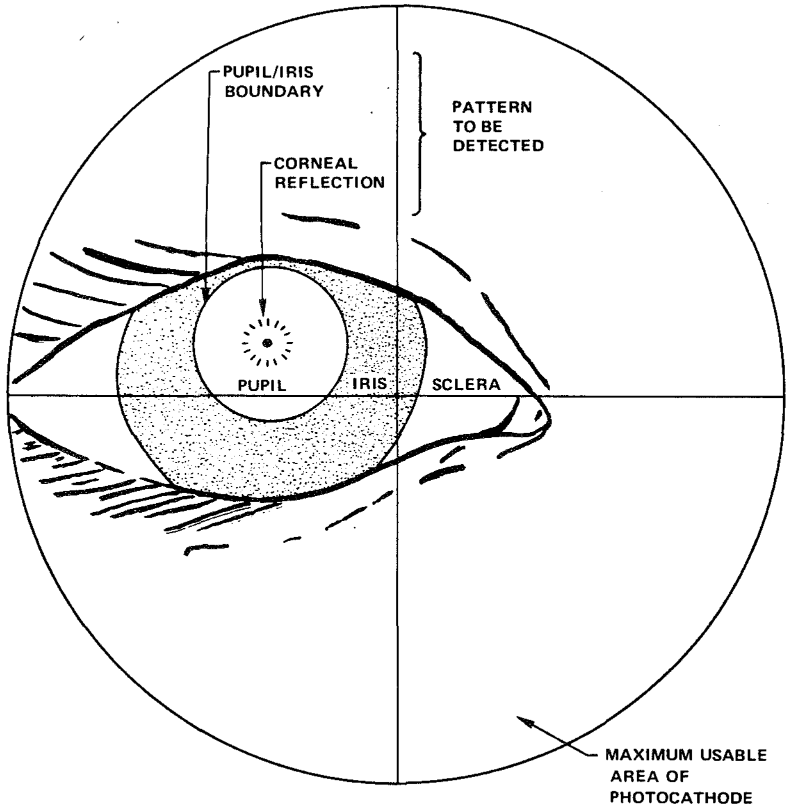


Figure 62 *Image of the eye on the photocathode of an oculometer. The relation of the pupil/iris boundary to the corneal reflection determines the direction in which the eye points.*[73]

optical concentration is demanded if the operator is not to be distracted by outside visual cues.

VOICE CONTROLS

Another control signal, the human voice, can convey a great deal of abstract control information to the machine. For example, if a voice control were combined with the oculometer discussed above, the operator would merely look at an object and verbally command the machine to pick it up, turn it over, or move to the spot where his gaze is next fixed.

The most primitive kind of voice control depends only upon the presence of sound—any sound—to activate a switch. Such voice switches do not discriminate between natural noises and commands from someone other than

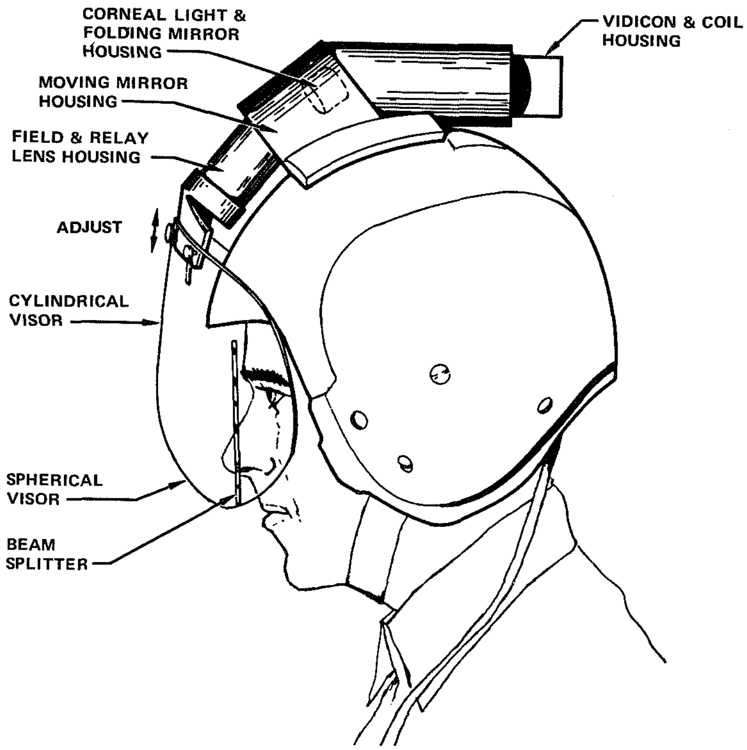


Figure 63 *The Honeywell concept of a helmet-mounted oculometer.*[73]

the operator. Somewhat more selective are voice switches that depend upon a certain tone, perhaps a whistle. When the control system can discriminate between different tones (whistles, again) the operator could actuate several different switches or even continuously control the setting of a control. The grip force of a manipulator hand, for example, might be made proportional to the frequency of a whistle. Voice controls of this type have not been applied to teleoperators, although a few experimental devices have been constructed to help handicapped persons.

A single word in the human language can convey much more than an on-off switch command. Consider the fact that one human can verbally direct another to carry out the most complex task—in fact, any task that might be assigned to a teleoperator. Why, then, cannot a human operator verbally direct the machine portion of a teleoperator to carry out any manipulatory task he has in mind? In terms of tomorrow's technology, he probably can; but today's machines can comprehend only the simplest spoken words. Once they understand the words in a command, though, they can carry out the command to the letter. To illustrate, it is not too difficult to build a machine that can comprehend and act upon verbal "stop" and "go" commands.

Stanford Research Institute, M.I.T., and several other organizations are exploring the technology of machines that understand the spoken word. Sheridan's group at M.I.T. is the only one currently applying this approach to manipulator control.[13] The basic manipulator commands are quite simple; at least at the lowest, most primitive level; viz., move wrist clockwise, close hand, etc. If this were not so, manipulators could not be controlled by simple switchboxes. The simple command "pick up," however, contains more information than that intrinsic in the flicking of a single switch. To pick an object up with a unilateral manipulator, several switches and their corresponding degrees of freedom may have to be activated. The human language moves easily from simple to complex commands, and today's machines are ready learners. The situation is analogous to the historical progression from the early machine-language programming of computers to the more and more abstract human-oriented instructions of Fortran and its descendants.

The first problem in voice control is, of course, speech recognition or the identification by the machine of the spoken word; that is, correlation of a train of sound patterns with known words in its memory. Once this association can be made, the computer can take over. The machine recognition of voice patterns is not within the scope of this survey. The reader should refer to the literature on the subject.[74,75]

At M.I.T. an English-language-controlled manipulator is being built using a cascade of three processes:

1. A sentence parser, which recognizes typed (not spoken) words and casts them into categories, such as named objects, goals, specific actions, adverbs, etc.
2. A semantic interpreter which operates on the structured statement so that it can "understand," i.e., decide upon unique subgoals.
3. A manipulation interpreter, which, given the understood subgoal, decides upon a sequence of primitive manipulator actions to achieve that subgoal. This process may make use of state-space algorithms, or heuristic techniques, such as those mentioned in Chapter 3.

Control of manipulation by English commands is in an embryonic state; no hardware has been constructed yet, although the reader will find many speech recognition devices described in the literature.

SPECIAL CONTROLS USED IN PROSTHETICS AND ORTHOTICS

An artificial limb is much like a manipulator but the amputee who operates it is at a great disadvantage because he has either lost all or part of the analogous flesh-and-blood limb. The amputee often has recourse to his remaining hand for actuating controls or he may employ his shoulder, his feet, and other muscles. Even a person who is almost totally disabled can manage to move his head or tongue or some portion of his body to initiate externally powered aids.

If the artificial limb is externally powered, perhaps by batteries or compressed gas, switches located somewhere on the body are the most common sources of control signals. Switches are simple, cheap, and reliable—as mentioned at the beginning of this chapter. They are also very limited in flexibility and proportional control is impossible. However, an artificial limb can be controlled rather well with a few simple switches. A joint on a prosthesis is essentially a four-state device, just one step more complex than the ordinary fixed-rate unilateral manipulator joint. According to Tomovic, the four possible states are: (1) locked, (2) increasing, (3) decreasing, and (4) free.[76] The final state is the one not found on ordinary unilateral manipulators. Proportional control is desirable in an artificial limb to improve manipulation and make its motion appear more natural. However, the simplest artificial limbs are generally the most successful because the ordinary wearer does not wish to be burdened with additional complexities.

The classical way to control artificial limbs is through shoulder shrugs and other bodily motions that pull cables attached directly to the artificial limb. The following general discussion applies to both self- and externally powered devices.

McLaurin has reviewed the different approaches to musculoskeletal control in prosthetics and orthotics.[77] He classifies the control motions into three groups:

1. The motion of one part of the body relative to another; for example, shoulder elevation, chest expansion, chin movement, humeral flexion, elbow flexion, finger motion, and many, many more.
2. The motion of one part of the body with respect to a fixed object; for example, head motion relative to a wheelchair, torso motion (joystick-fashion) relative to a chair, and, of course, the eye controls introduced earlier.
3. The motion of parts of the body relative to space; for example, head motion relative to local gravity and head motion that causes gyros to generate a control signal.

Many harnesses and special cables have been devised to help an amputee control and actuate an artificial limb without external power.[78] The figure-8 harness shown in Fig. 64 represents an example. The cable that runs from the harness down to the arm is called a Bowden cable. On occasion, the control cables are surgically connected to the wearer's muscles in an operation called "cineplasty."

Wearer-actuated artificial limbs have been in use for centuries. But now that compact sources of power have been developed, interest has turned to the so-called externally powered artificial limbs and orthotic devices. The most common sources of power are electrical, pneumatic, and hydraulic. If the wearer of the prosthesis has one good arm, the requisite switches or valves may be located in his pocket or attached to his body where they are readily accessible. Switches have sometimes been located in the shoe, when the wearer did not want to be too obvious in controlling his prosthesis.

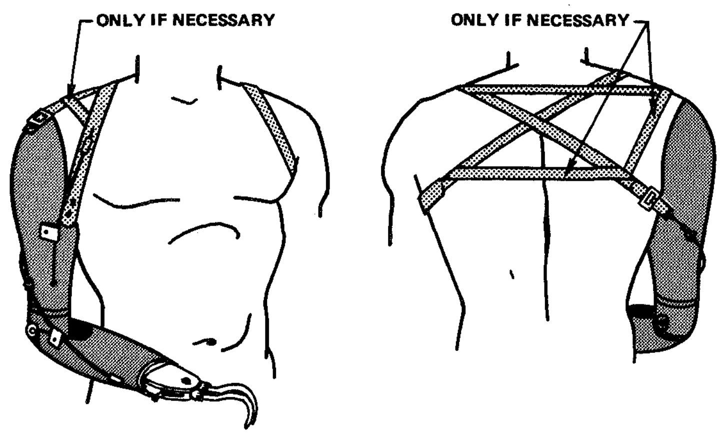


Figure 64 *An above-elbow artificial arm with a hook-type hand. A "figure 8" harness is used here. (Courtesy of E. Murphy, U. S. Veterans Administration.)*

Muscle-bulge switches are also employed, but like the shoe switches these control only one degree of freedom or one speed unless logic circuitry is added that translates coded switch signals into more sophisticated motion; i.e., two pulses, slow; three pulses, fast; etc. Each controllable degree of freedom might have a digital address; three- or four-level commands might be transmitted, too. But such codes are generally too much trouble. A few simple on-off switches are the rule.

When both arms are shrunken and deformed, as they are in many thalidomide cases, special switchboxes can be installed where they can be manipulated by the deformed limb and hand (the phocomelic digits).[79] Figure 65 shows a five-year-old thalidomide child with two artificial electrically actuated limbs built by Northern Electric Company, Ltd., in Ottawa. Later, the electric motors were replaced by a hydraulic actuator in a search for lighter weight and smoother operation.[80] Control for the hydraulic Northern Electric arm is provided by a lever-type selector valve that activates one of eight degrees of freedom, plus a switch that controls the direction of motion (Figs. 66 and 67). The Northern Electric hydraulic arms have been very successful. One patient can even write crudely with the prosthesis.

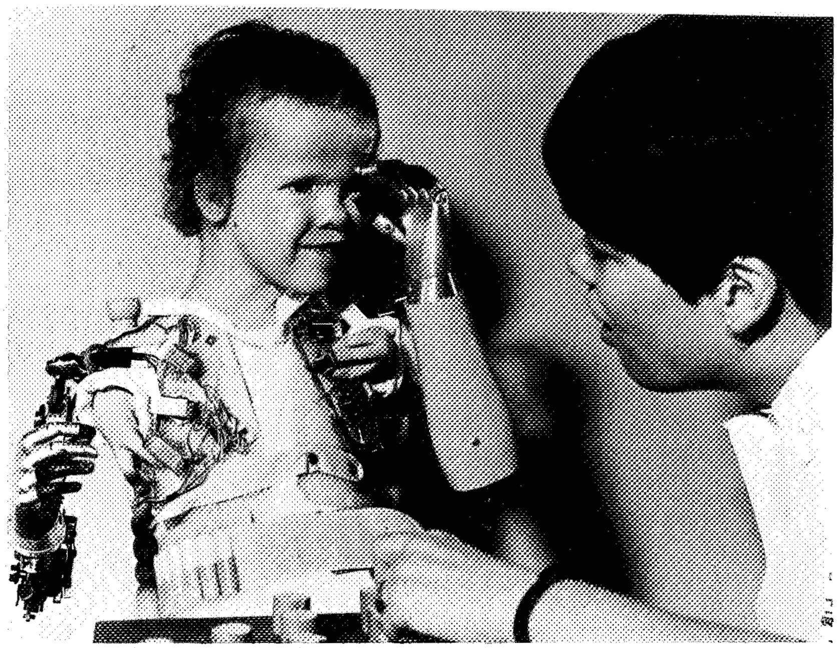


Figure 65 *The Northern Electric electric arm. Note the switches actuated by the fingers of the subject. (Courtesy of Northern Electric Co., Ltd.)*

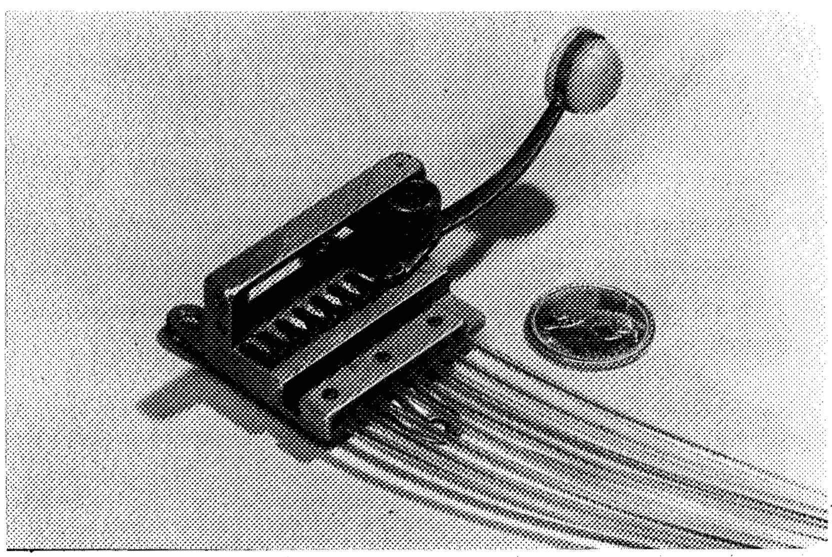


Figure 66 *The eight-way control-valve select lever employed on the Northern Electric hydraulic arm. (Courtesy of Northern Electric Co., Ltd.)*

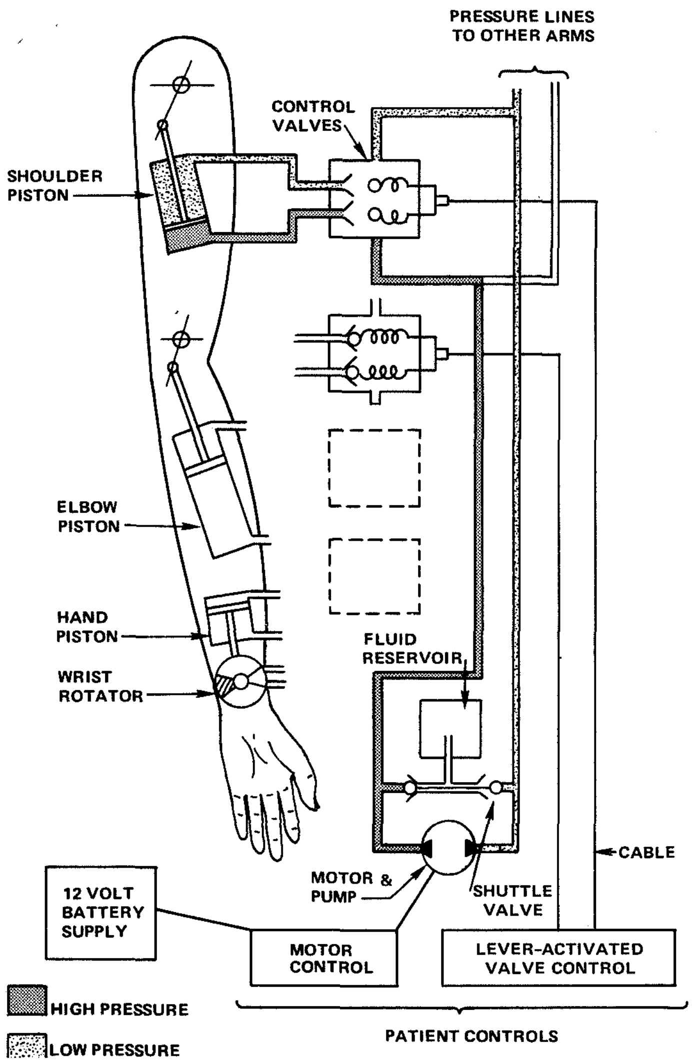


Figure 67 *Control system for the Northern Electric hydraulic arm. (Courtesy of Northern Electric Co., Ltd.)*

The Northern Electric controls described above are representative only. A large literature exists that describes many different varieties of switches for prosthesis control.[81]

When the hands cannot be employed at all for switch control, the tongue turns out to be surprisingly responsive and effective. Many different types have been built. Figure 68 portrays a seven-lever tongue control built by Rancho Los Amigos Hospital for high-level paralytics confined to wheel-

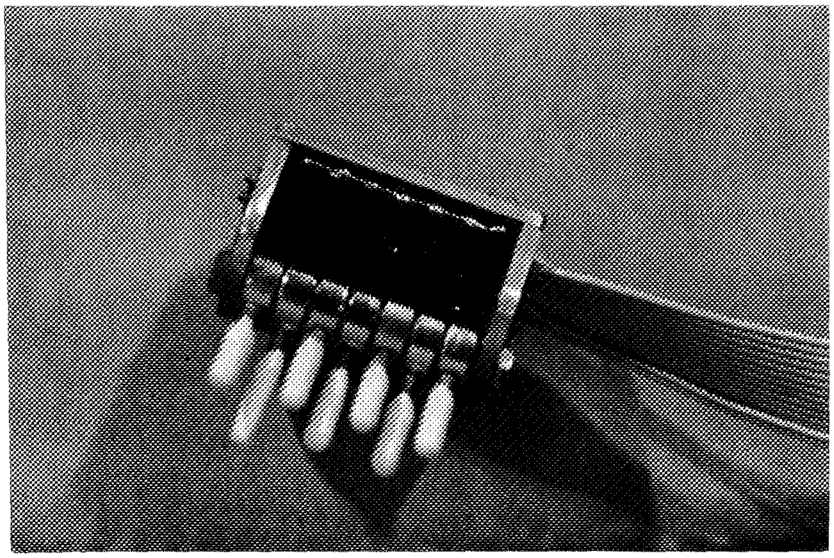


Figure 68 *A tongue switch. Each "toggle" is a three-way switch. (Courtesy of J. Allen, Rancho Los Amigos Hospital.)*

chairs.[82] Each switch has three positions. Much more elaborate *joystick-like* tongue-control devices have been designed wherein the tongue "manipulates" various levers and buttons. Proportional controls have been built into some of these devices.

Proportional or rate control can be provided for artificial limbs through pressure-sensitive devices, such as strain gauges in the teeth and even blowing and sucking controls. Although rate controls run a poor second in popularity to on-off and three-level switch controls, they do emphasize the remarkable flexibility and adaptability of parts of the human body to help the hands and arms in the control of complex machines like teleoperators.

The switches and proportional controls activated by muscle bulges are of three basic types: carbon, photoelectric, and strain-gauge.[83] The carbon transducers operate on the same principle as telephone transmitters; carbon granules are sandwiched between two electrodes. Muscle pressure on the electrodes will decrease the electrical resistance between the electrodes. Photoelectric transducers can be made in several configurations, one of which is illustrated in Fig. 69. The fundamental idea here is to reduce (or increase) the quantity of light received by the photocell as the actuating muscle is flexed. Strain gauges (Fig. 70) can be attached to muscles to yield a signal roughly proportional to the muscle bulge.

Except for the artificial arms that are controlled directly by cables connected to body harnesses or actual muscles, there is little or no force feedback present in the schemes discussed above. Neither is there an

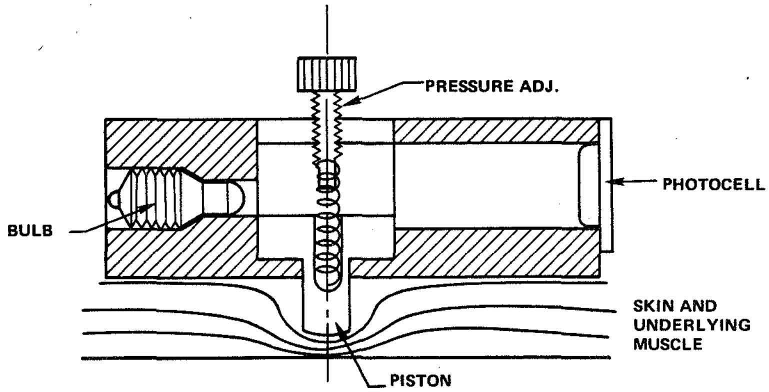


Figure 69 *A photocell transducer for muscle-bulge control.*[83]

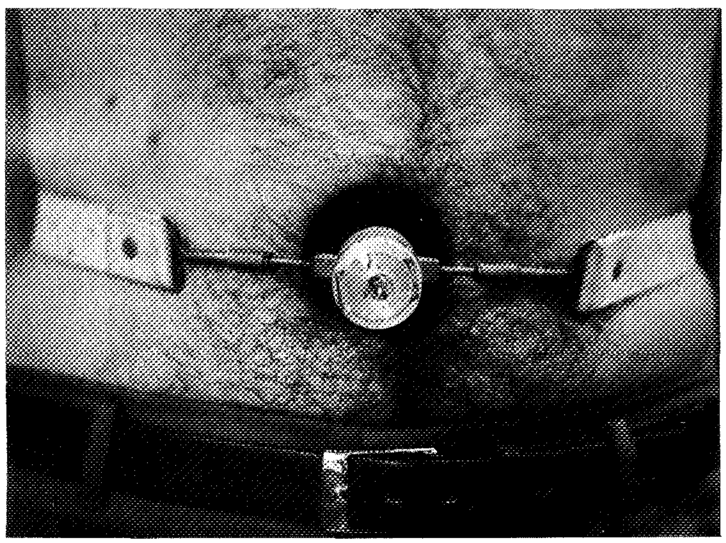


Figure 70 *A strain gauge transducer attached at an abdominal site. (Courtesy of J. Lyman, University of California at Los Angeles.)*

analogous limb that would be able to interpret the feedback in most cases. This is a severe handicap because objects often fall from the grasp or are perhaps broken when the prosthesis wearer cannot feel the force he exerts. This deficiency can be compensated for to some extent by building a closed-loop control circuit that bypasses the operator. Salisbury *et al.*, at Walter Reed Army Medical Center, have installed piezoelectric sensors in the fingers of an artificial hand. These sensors detect the vibrations created when two surfaces slide over one another. Slippage noises are converted into commands that cause the hand grip to increase until slippage stops.

These examples represent only a sampling of the control technology that has built up during the years around artificial limbs and orthotic devices. Although these prosthetic and orthotic devices are included with manipulators, walking machines, and exoskeletons under the definition of the teleoperator, there has been relatively little intercommunication.

ELECTROMYOGRAPHIC (EMG) CONTROL

Muscle activity is basically electrical in nature. When electrodes are attached near or in any of man's striated muscles, muscle flexure generates electrical signals we can pick off for control purposes. These signals are variously termed electromyographic (EMG), or myographic, or muscle-action potentials (MAPs).

According to Alter, the control potential of EMG signals was recognized by Norbert Wiener in the early 1950s.[84] The suggestion was quickly followed up in Britain and Russia, where prototype EMG-controlled prostheses were constructed prior to 1960. The United States has generally lagged behind in this field, although Alter's bibliography demonstrates that American interest in EMG controls has increased rapidly of late.

Most of the work described below was carried out with the application to prosthetic and orthotic devices in mind. However, normal people generate EMG signals, and these may eventually be employed for controlling other kinds of teleoperators. Tiny electrodes, for example, may turn out to be much smaller and more comfortable to use than the controls described in the preceding sections. One can even visualize gloves or tightly fitting jackets, even space suits, with built-in electrodes that an operator would don to control a teleoperator with many degrees of freedom. In this concept, the motions of the operator would be faithfully duplicated by the actuators, located perhaps in a hot cell or on the Moon. Such visions are far off, however, for the EMG state of the art is still rather primitive.

There are three classes of electrodes which may be used to pick up EMG signals: skin-surface types, types which pierce the skin, and types completely implanted in the body.[85] Surface electrodes are obviously the easiest to install and remove (Fig. 71). Their disadvantages include weak signals—due to the high impedance of the skin, which can be reduced somewhat by electrode pastes—and the surface electrode's tendency to shift, producing "artifacts"; that is, unwanted electrical disturbances. There is also "crosstalk" from nearby muscles. Electrodes that pierce the skin may be placed just below the skin (subcutaneous) or they may penetrate the muscle itself. The skin impedance problem is bypassed by this kind of electrode. The intramuscular electrodes can pick off signals from different muscles or even from different parts of the same muscle. Electrodes that penetrate the skin still have a tendency to wander a bit; they may break off, too, leaving a piece of metal in

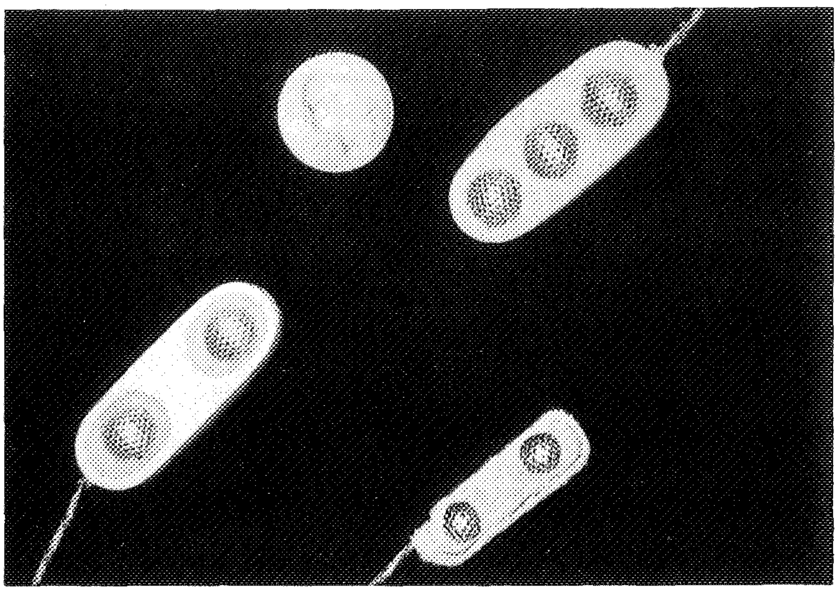


Figure 71 *Surface electrodes for detecting EMG signals. (Courtesy of W. Waring, Rancho Los Amigos Hospital.)*

the operator. Further, the electrode site is a source of irritation and potential infection. Surgically or hypodermically implanted electrodes that will survive the bath of corrosive body fluids and not irritate the operator are difficult to design. Surface and skin-piercing electrodes have been employed most frequently in EMG work.

All of the striated muscles are potential sites for control electrodes. In the case of the normal person, the muscle selected would ordinarily be analogous to the motor driving the same degree freedom in the teleoperator; the biceps, for example, might control a manipulator elbow joint. But almost any muscle can be trained for EMG-control purposes. Shoulder muscles are used for controlling artificial arms in cases where the natural muscle site no longer exists.* The teleoperator designer of the future may wish to seize upon this attribute for the control of nonanthropomorphic degrees of freedom; say, the control of wrist extension via a shoulder-muscle electrode. Even more exciting is the discovery that a human operator can voluntarily control single motor units in a muscle, a fact that potentially increases the number of available EMG control sites by a large factor. In other words, the number of output signals under conscious, voluntary control of the operator can be many times greater than the number of physical degrees of freedom. Despite

*In controlling orthotic devices, the natural muscle may still produce useful EMG signals even though the real arm cannot be moved voluntarily.

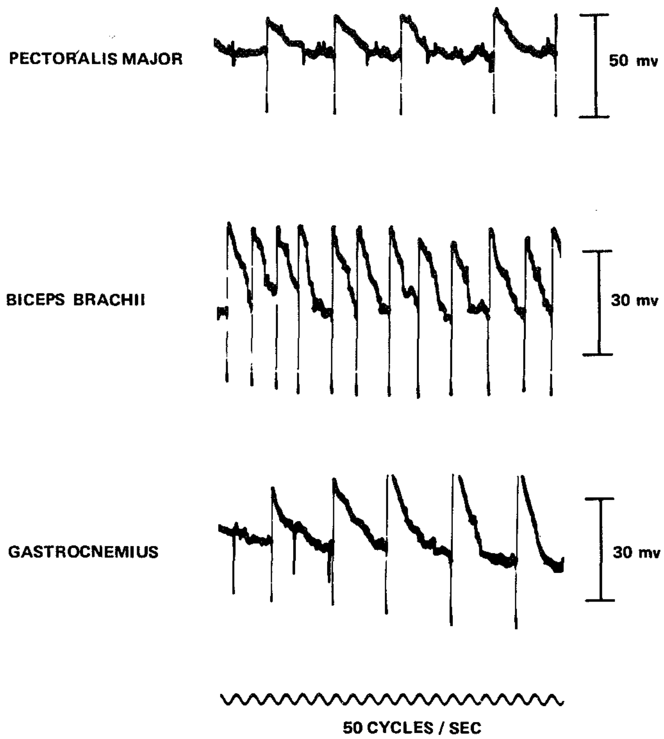


Figure 72 *Recordings of EMG signals from a normal subject.*

these promises of future enhanced control through EMG, contemporary development programs are oriented toward making simpler systems work well, especially those destined for handicapped persons.

Let us look more closely at the EMG signals; when a muscle is flexed, electrodes nearby or embedded in the muscle itself record the summation of separate fiber action potentials.[86] In this sense, an EMG signal is an "interference pattern" resulting from the addition of numerous signals from separate fibers. The observed signal obviously depends upon the location of the electrodes. In spite of all the variables, normal muscles produce characteristic signal patterns (Fig. 72). Three parameters describe these signals: amplitude, spike width, and spike frequency. Amplitudes are usually less than 50 millivolts peak-to-peak; while the spike width is measured in milliseconds. Spike frequency or repetition rate varies greatly with the muscle selected, as indicated in Fig. 72. A plot of power vs. frequency (the signal spectrum) is shown in Fig. 73 for two different muscle loads. It is the change in signal amplitude with muscle load that allows us to provide proportional EMG control to teleoperators. As muscle contraction increases, there is also an overall increase in repetition rate; another potential source of control data.

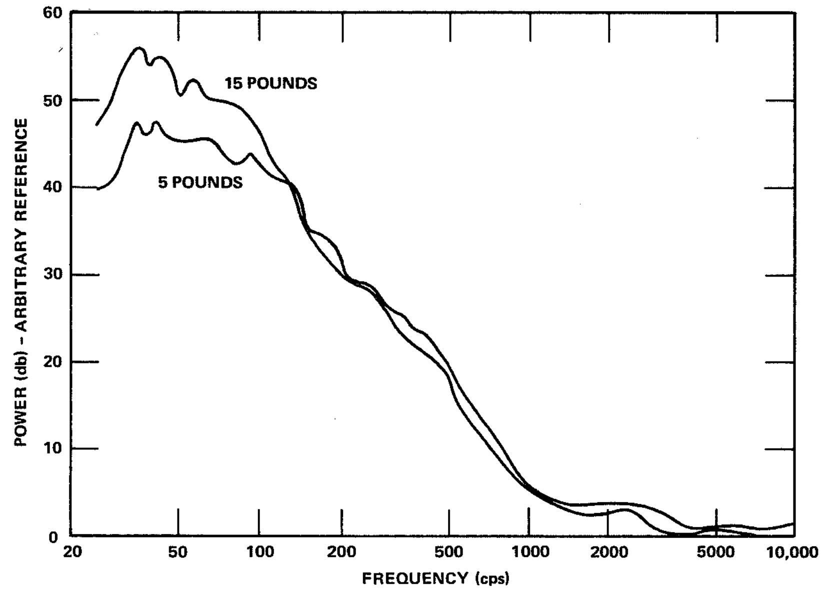


Figure 73 *Typical power spectra for surface-electrode EMG signals.*

Superficially, EMG signals would sound almost ideal for teleoperator control. EMG signals are certainly more convenient than, say, tongue switches for a handicapped person. They are also lighter and more comfortable than restrictive harnesses. Furthermore, reasonably accurate proportional control has been demonstrated. On the other hand, electric razors and other applicances may seriously interfere with EMG signals as does the crosstalk from other muscles. Some wearers of EMG-controlled devices feel that EMG offers less "positive" control than switches. Lyman, who has made a systematic study of the performance of EMG systems in skilled manual control tasks, found that the operators were easily fatigued and that considerable concentration was required, particularly when more than one degree of freedom was being controlled.[87] The poor reliability of bioamplifiers has also been a major problem area. Summarizing, practical EMG control is beset with development problems.

Of the many EMG-controlled prostheses, we describe Bottomley's "myoelectric hand"[88] and a hand built by A. N. Skachkov[89] of the U.S.S.R.

The Bottomley hand fits over the forearm of the amputee; two surface electrodes (Fig. 74) are fitted into the socket. To reduce crosstalk, signals from opposing forearm muscles are employed. The block diagram of the circuitry is illustrated in Fig. 75. Strain gauges in the hand yield a signal proportional to the force generated on an object by the hand; this signal in this local loop opposes the EMG signal and will cancel it out before the hand

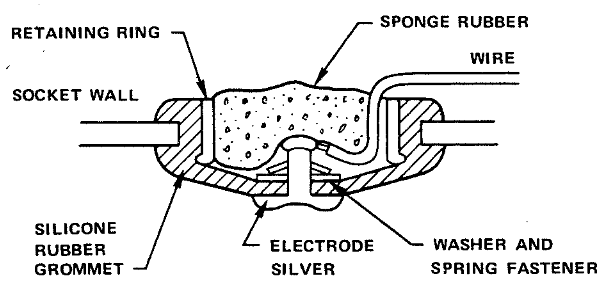


Figure 74 *The surface electrode used with the Bottomley EMG-controlled hand.*[88]

can damage the object or itself by exerting too much force. Of course, the wearer can increase his grip upon an object by flexing his control muscles more; the motor will then operate until the strain-gauge signal again cancels out the EMG signal.

The Skachkov hand is quite similar to that of Bottomley; however, the feedback device is different and rather interesting (Fig. 76). Instead of employing a local feedback loop, the wearer is brought into the loop by forcing him to monitor a vibratory feedback, which is proportional to the pressure on the thumb of the artificial hand. The purpose of the feedback is the same as that in the Bottomley hand.

The subject of feedback to the wearer leads to the frequently suggested possibility of feeding back electrical signals directly into the operator's muscles so that they will "know" intrinsically just what force the teleoperator is exerting. This would be an enviable kind of force feedback, but we have little knowledge as to how to put the idea into practice at the present time. The great hopes for EMG control stem from the philosophical observation that the human body is itself an electrical "machine" and so are many teleoperators. Should there not be many more intimate ways of coupling such similar equipments?

HARDWARE AND SOFTWARE FOR SUPERVISORY CONTROL

Control equipment in supervisory control consists of both hardware (typewriters, computer consoles, and devices like light pens) and software (computer programs, tapes, analog records, etc.). Supervisory control hardware and software are in the experimental stage today.

Two groups have developed computer-controlled manipulators:

1. Case Western Reserve, where NASA and the AEC have sponsored work potentially leading to the semiautomatic disassembly of radioactive nuclear rocket engines.[7,90]

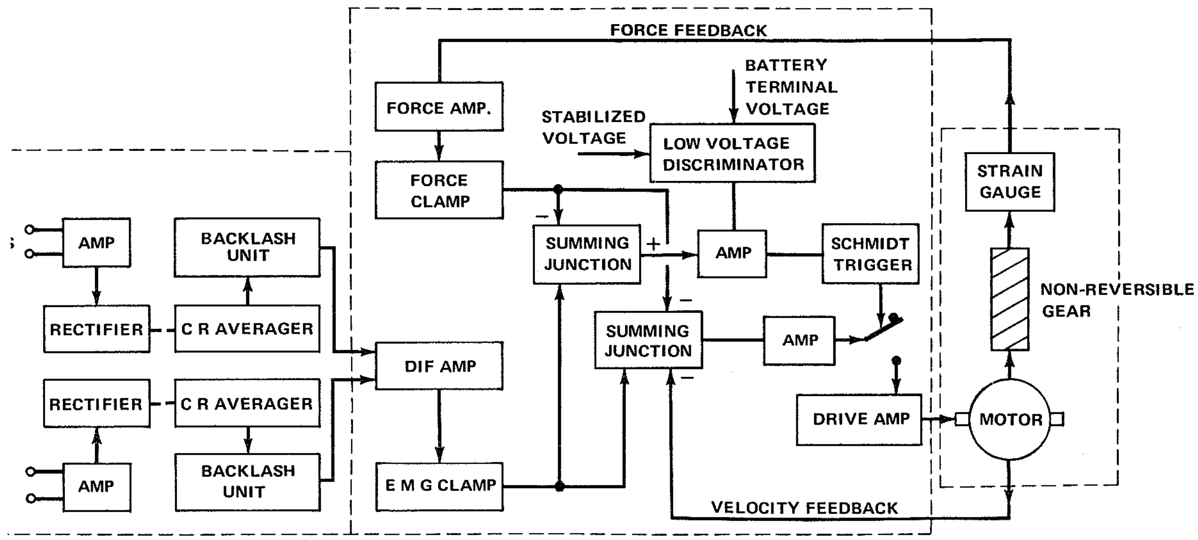


Figure 75 *Block diagram of the control circuitry for Bottomley's EMG-controlled hand.*[88]

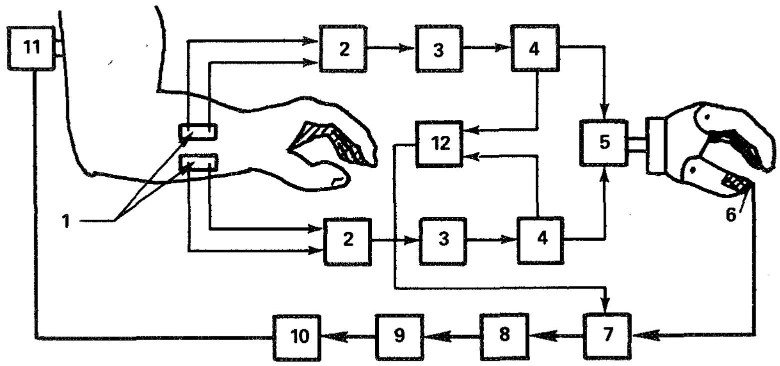


Figure 76 *Block diagram of the Russian EMG-controlled prosthesis.*[89] *(1-Electrodes, 2-Amplifier, 3-Discriminator, 4-Amplifier, 5-Motor, 6-Pressure transducer, 7-Amplifier, 8-Pulse generator, 9-Pulse shaper, 10-Amplifier, 11-Vibrator, 12-Summing circuit)*

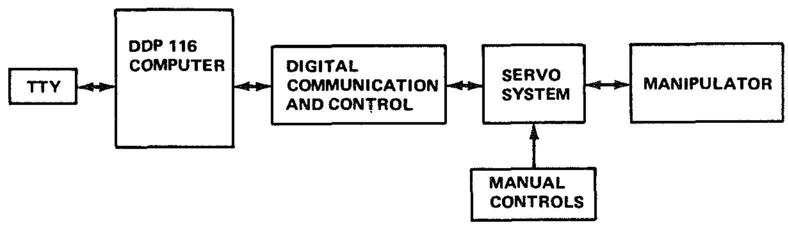


Figure 77 *Block diagram of the Case computer-controlled manipulator. The General Purpose Interface (GPI) described in the text bridges the interface between the computer and the manipulator.*[90]

2. M.I.T. where general man-machine control problems are being attacked in both Sheridan's group (NASA-DOD support[91]), and Project MAC (DOD support[92]).

A typical system configuration of the Case computer controlled manipulator is illustrated in Fig. 77. The human operator can make inputs at two spots: the teletypewriter (TTY) and the conventional manual controls. The TTY, of course, is the input point for supervisory control instructions, which may be extremely simple incremental motion instructions or a command to carry out a complex subroutine of instructions stored in the memory.*

Following the path of supervisory control information—horizontally from TTY to Manipulator in Fig. 77—we see that the operator must first know what sort of instructions to type for the computer on the TTY; next,

*A typical supervisory control subroutine employed in the Case system was described in Chap. 3.

the computer output must be converted into electrical voltage signals that will drive the manipulator joints the proper distances in the proper directions. The interface between the operator and computer is bridged by the Teletype Executive Control Program (TTY Exec); while the computer directs the manipulator through the General Purpose Interface (GPI) Unit.

In the TTY Exec approach, all subroutines are initially stored in the computer's memory. The operator must specify a basic positioning or path-control algorithm as well as specific distances and other data related to the desired manipulator action. The following example is from Beckett:

Desired action: The manipulator hand should move 7.5 inches in a straight line along the direction in which the hand points.

Actions:

1. The operator types a V and the TTY Exec first calls the IDST subroutine (Fig. 78).
2. The IDST subroutine types the letters DIST and then waits for the operator to specify the distance to be moved in inches. (Note: the IDST subroutine contains instructions that enable the computer to understand the specific distances typed by the operator.)
3. The operator types 7.5, followed by a carriage return.
4. The IDST subroutine stores the figure in a memory buffer.
5. The TTY Exec (as instructed by the letter V typed first) now calls the VECTOR subroutine, which produces a series of signals that will drive the manipulator motors the required amounts—provided the signals are translated into motor voltages in the GPI.

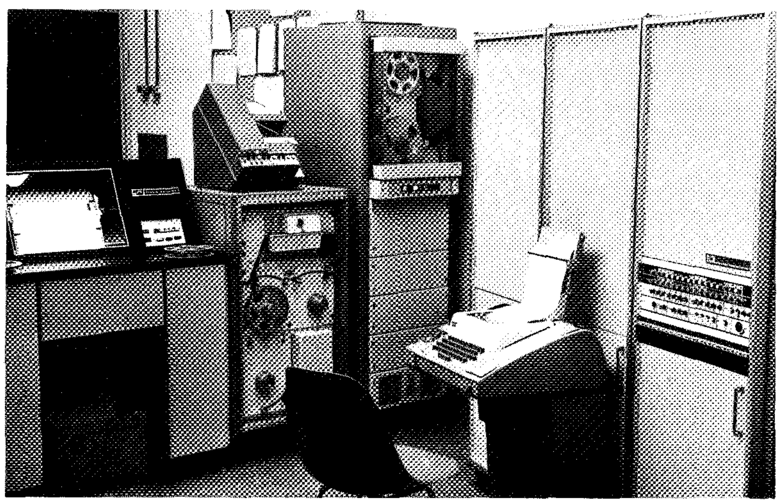


Figure 78 *The teletypewriter is a common input device for computer-controlled manipulators. (Courtesy of Case Western Reserve.)*

The General Purpose Interface (GPI) is too complex to be described here; the reader is referred to Taylor's report.[90] The GPI provides a communication and control link between the computer and an arbitrary external machine (a manipulator here). It is designed to translate computer signals into basic manipulator control voltages. Address and function decoding are done within the GPI and it also provides status information lines to let the computer and operator know the current manipulator configuration.

Summarizing the Case setup, the operator types abstract symbolic commands and specific data on the TTY. Using its programs and subroutines the computer converts the commands and data into a series of signals which, in turn, are converted by the GPI into the required manipulator voltages.

Supervisory control reaches its ultimate development in the fully developed robot; that is, a machine that carries out high-level, abstract commands without human assistance at any primitive levels of action. The robot developed by Stanford Research Institute (SRI) under DOD sponsorship[17] is not a teleoperator per se because it manipulates nothing and rolls rather than walks (pedipulates) (Fig. 79). Nevertheless, arms and hands *could* be added and operated within the general hardware/software framework. In actuality, the SRI robot is a harbinger of future teleoperator technology.

The SRI scientists suggest that their robot (or any robot/teleoperator) will eventually be able to operate at four levels of control:

1. The immediate-action level, where the operator directly activates the motors and sensors. (This mode of operation is equivalent to the operation of unilateral manipulators by a switchbox. In other words, no supervisory control exists.)
2. The tactical level, where the robot solves simple problems in navigation and locomotion without the help of the operator. (The VECTOR subroutine employed by the Case computer-controlled manipulator falls in this category.)
3. The strategic level, where the robot finds specified objects and relocates them. (The Case and M.I.T. computer-controlled manipulators can carry out supervisory instructions of this type.)
4. The problem-analysis level, where the robot translates a high-level command into a series of subtasks according to some criterion of performance.

The SRI robot is controlled through a teletypewriter, just as the Case manipulator (Fig. 80). There is also an analogous computer plus its software (programs and subroutines). The computer-robot interface is intimate and specialized, not general-purpose like the Case GPI. While the Case system has status indicators, it does not have the full array of kinesthetic sensors

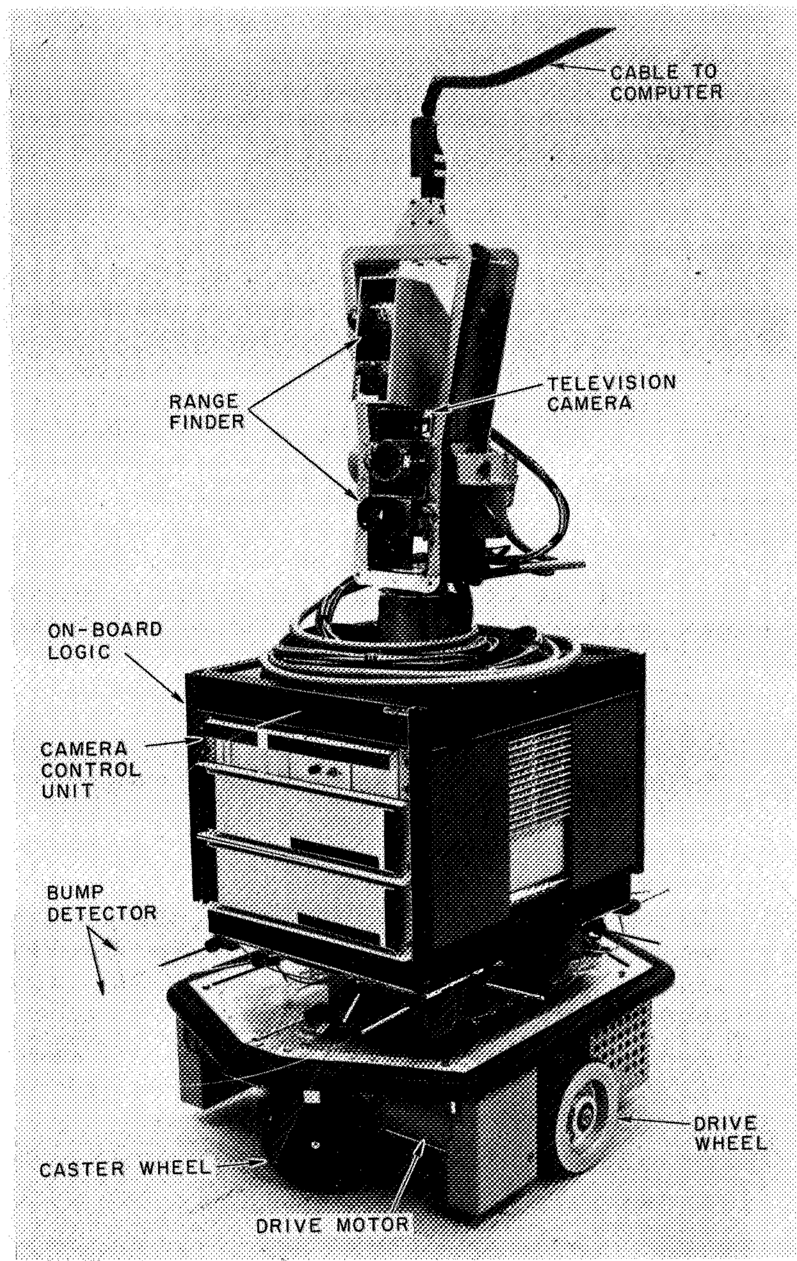


Figure 79 *The SRI robot. While this robot does not have the arms and legs needed to qualify as a teleoperator, its autonomous functions may eventually be incorporated into teleoperators. (Courtesy of C. Rosen, Stanford Research Institute.)*

possessed by the SRI robot. The SRI robot uses both the visual and kinesthetic feedback in local control loops.

Using visual feedback through its TV and kinesthetic data (obtained from bumping objects in its environment) the robot can construct a model of its environment. The model includes its own location as well as the positions,

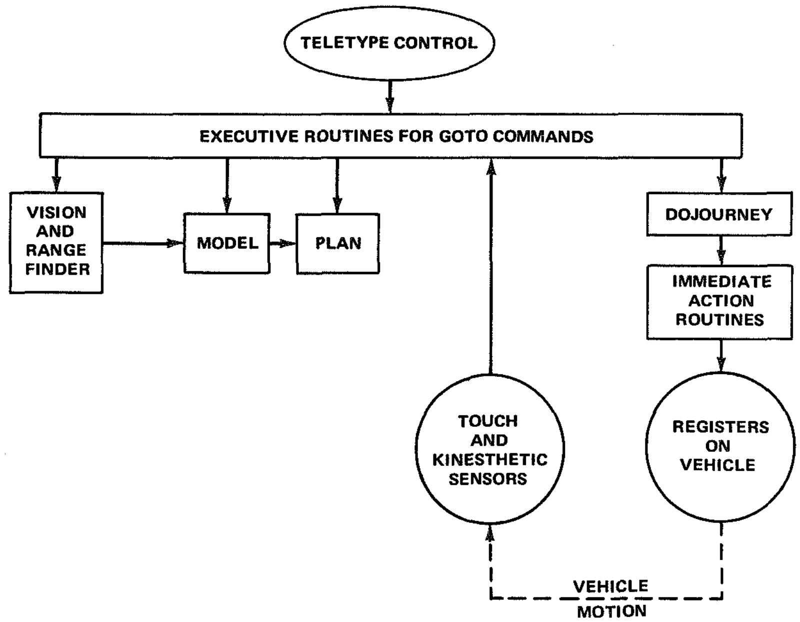


Figure 80 *Control plan for the SRI robot. Note the local control loops. DOJOURNEY is a specific robot program.*[17]

orientations, and in some cases identities of the objects. The robot can reconnoiter its surroundings itself—a valuable property for a teleoperator operating, say, beneath the sea, where feedback to the operator may be sparse. In most computer-controlled manipulators, obstacles to be avoided must have their coordinates placed in the computer's memory by the operator; not so with the SRI robot.

A number of lower-level subroutines have already been successfully tested with the SRI robot. A typical immediate-action-level command is CALL MOVE (N, HANDLE). This command moves the vehicle forward (+) or backwards (–) N 32nds of an inch. A bump can interrupt this subroutine, in which case HANDLE (a sort of register) will be set at the number of motion increments not actually completed. Like all other computer-controlled devices discussed in this book, the SRI robot moves in a quantized fashion.

The GOTO executive subroutines operate at a somewhat higher level. They take the robot from one point to another, using its model of the environment to help it avoid obstacles. More complex programs are being written for the robot, such as that described in the flow chart of Fig. 81.

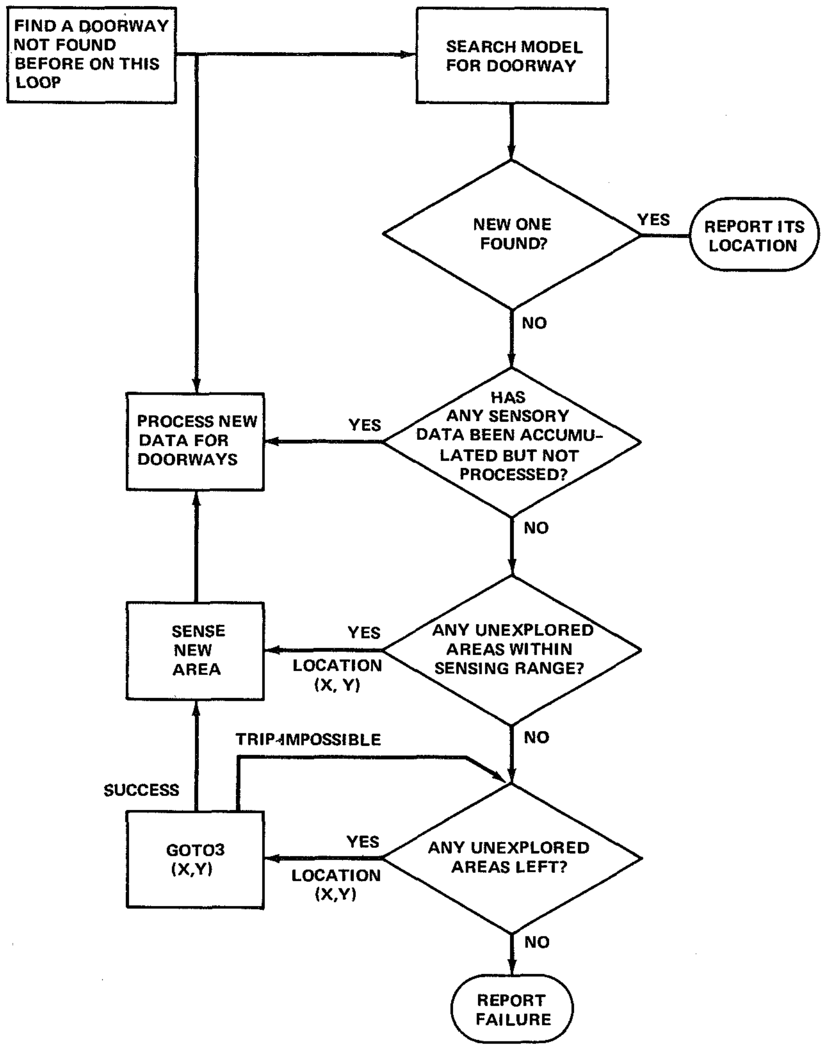


Figure 81 *Flow diagram for a more advanced program proposed for the SRI robot. A similar program could be used by a teleoperator searching for a specific object.*[17]

Clearly, by building upon a foundation of simple autonomous (primitive) functions and utilizing its feedback data, the SRI robot and its descendants will be able to carry out more and more generalized, higher-level commands from the human operator. As stressed frequently in earlier chapters, teleoperators are also following this path toward greater autonomy.

Chapter 6

DISPLAYS

TELEOPERATOR DISPLAYS

In the broadest sense, a teleoperator display is the output station for all sensory information fed back to the operator. The display is the output counterpart of the input hardware described in the last chapter. Together, controls and displays connect man to machine and vice versa; they are interface devices (Fig. 8).

The word "display" connotes a pictorial, visual view of some scene or situation. Control engineers broaden the meaning to include abstract and symbolic displays, which represent scenes or situations in less natural terms, such as a digital distance reading or a stylized manipulator configuration. In teleoperator engineering, the concept of a display must be expanded to include the complete panorama of man's senses; past, present, and predicted future; couched in anthropomorphic or abstract language. A TV scene of the interior of a hot cell is a display; but so is the force feedback in the arm of an electric masterslave; so is a warning buzzer signaling that a joint's limit of travel has been reached.

Display design is a field of great importance in the engineering of aircraft, manned spacecraft, and submarines, where the operator must be aware of a great deal more than he can perceive looking through a window or porthole. In fact, windows and portholes are not used at all on some vehicles; instead, a "picture" of the environment is drawn by radars, sonars, and other sensors.

Teleoperators are manipulatory and sometimes pedipulatory and mobile; vision is crucial to good performance in most cases; force feedback and tactual feedback are desirable where they can be obtained at a reasonable price. The other senses, such as sound, are not nearly as important. Teleoperator displays in use today differ little from those in advanced aerospace and undersea vehicles. In fact, they owe much to the display theory and hardware developed for these vehicles.[93,94]

Ideally, a teleoperator display would show the environment of interest (including the objects to be manipulated, local temperature, and other factors) and the present position or status of the teleoperator. This type of information gives the operator a seat-of-the-pants feel for the situation.*

*Teleoperator technology will eventually be able to supply multiple operator feedback terminals so that many scientists could participate in, say, remote lunar exploration; although only one person would be the true operator, of course.

Good displays project the operator into the place where his ersatz hands and legs are working—he *identifies* with the situation. We have stressed in earlier chapters that manipulation also requires planning and strategy formulation. We therefore must make room in our definition of displays for portraying *executive* information that will help the operator make decisions. Two special types of displays that fall in this category are the predictor and historical displays; one looks into the future using known physical laws; the other searches the past for relevant information. Teleoperator displays can and probably will be much more generalized than the hot-cell windows and closed-circuit TV typical of most extant teleoperator applications.

Display engineering has been largely intuitive in the past. In the case of teleoperators, the basic tenet has been to make the display as real as possible; that is, to duplicate the sight, sound, and feel of the task as faithfully as possible. This philosophy is a natural corollary to the assertion that teleoperator controls should be as anthropomorphic as possible. Both of these views are being challenged today.

While no formal teleoperator display theory exists, some progress has been made recently in formalizing display theory for use in conventional manual control situations; i.e., aircraft and undersea craft. Kelley's book[27] and a recent paper by McRuer and Jex[94] are representative of this work. Most display theory deals with forced-input tracking situations and offers little to the designer of a teleoperator display.

Conventional display theory does offer a checklist of points to consider and pitfalls to avoid in teleoperator display design:

1. Noise seriously degrades displays. A reasonable signal-to-noise ratio must be obtained in all sensory dimensions.

2. The effectiveness of a display is reduced by intermittence; that is, the reduction in time intervals when the display is active or sensed by the operator.[95] This factor applies to the time-multiplexing of display information and the sampled-data aspects of the operator as he shifts his attention from one display to another.

3. Time-delayed feedback is highly disruptive as mentioned in Chap. 3. Predictor displays may minimize this effect.

4. Visual display parameters of magnification, framing, color, dimensionality, contrast, brightness, etc. must be considered,[96] although few objective data are available to guide the designer.

The human factors scientist obviously has a great deal of experimentation ahead before firm guidelines emerge for teleoperator display engineers. The make-it-anthropomorphic school is supported by intuition, but intuition has been proven false in the past. The fact is we really know very little about engineering teleoperator displays.

NATURAL VISUAL DISPLAYS

Although a surprising amount of manipulation can be carried out by the sense of feel alone—blind workers, for example—sight is by far the most important human input channel. In some manipulator and pedipulator tasks, the operator sees his work and its environment directly or perhaps through windows, such as those in hot cells and submersibles. Calling a hot-cell window a display may stretch the definition a bit; but the hot-cell window is a processor of optical data. A hot-cell periscope, or fiber optics device, which provides the manipulator operator an indirect view of his work, fits the definition of display even better. A periscope processes optical information, often magnifying the image, and presents the hot-cell interior to the human eye at its focal plane.

We term direct and indirect viewing systems "natural" because there is no intentional distortion of the scene. In natural visual displays, the object is to make the view presented to the operator as realistic as possible.

Another natural viewing system is closed-circuit television. In TV, the scene is disassembled and then reconstituted electronically at the display. In between, there may be considerable data processing, particularly in those television systems employed in astronautical ventures. Despite these opportunities, the guiding philosophy for most TV displays is "make it natural." In the backs of our minds, however, we should remember that in TV systems resides the potentiality for creating unnatural, perhaps symbolic, displays. To illustrate, signals from a TV camera might be combined with other sensory data, say, manipulator joint position data, to draw an abstract three-dimensional picture of the scene, somewhat after the fashion of air-traffic-control displays.

With this introduction, the reader should turn to Ref. 1, Chap. 6, for a discussion of the engineering features of natural visual displays and the sensors associated with them. The remainder of this chapter deals with symbolic visual displays and displays involving senses other than sight. Reference 1 dealt with teleoperator sensors and displays in use today; our present purpose is to introduce some thoughts about teleoperator displays of the future.

SYMBOLIC AND ABSTRACT VISUAL DISPLAYS

Once it is admitted that natural, pictorial displays convey only part of the information an operator desires, the way is open to symbolic displays. The word "symbolic" is used here to mean non-pictorial. A simple warning light indicating that a manipulator limit of motion has been reached for a manipulator is a symbolic display because an "on" light is a code signal understandable to the operator—a signal conveying far more than one bit of information.

The basic function of a display is to provide the operator with enough information to make decisions; this information need not be pictorial to be useful. In fact, manipulation can be accomplished without natural, pictorial feedback at all. Computer-controlled manipulators never "see" their targets at all. Conceivably, a human operator could manipulate objects given enough force and tactual feedback plus a good repertoire of executive signals, although performance might suffer considerably without vision.

Besides warning lights and other status signals, what other kinds of symbolic visual displays might be useful in teleoperator work? Perhaps the most obvious type would be an abstract portrayal of the working environment, its targets, and the teleoperator arms and hands—a substitute for a natural view, which might be unobtainable. The scene could be drawn on a cathode ray oscilloscope tube (CRT) in stylized fashion, showing the manipulator and its targets vividly in three dimensions, possibly color-coded for easy identification, noise could be suppressed, and target data could be inserted verbally near the target image on the CRT (the air-traffic-control example again) (Fig. 82). The Computer Image Corporation has been

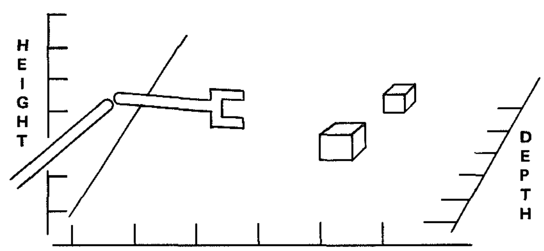


Figure 82 *A possible abstract visual display indicating the configuration of a teleoperator and the external environment. Such a display need not be drawn from visual data alone; i.e., sonar, radar, and status sensors can be employed.*

pioneering this type display. Such an abstract, coded representation might be much easier to work with than a natural view of the scene. Furthermore, this kind of display could be drawn from many different kinds of sensory inputs: iconoscope, radar, sonar, and, of course, status data. There would certainly be anthropomorphic aspects to an abstract display in terms of spatial correspondence, but we have no experimental assurance that anthropomorphism is required.

Few symbolic or abstract teleoperator displays have been built yet, so we continue primarily in a prophetic vein, buttressed by some anticipatory work done here and there for other applications.

Symbolic displays are part and parcel of everyday life; viz., fuel gauges and speedometers in automobiles. A symbolic approach to manipulation is not hard to imagine, though there is no proof that it would be effective. Most manipulatory tasks can be described in terms of seven dimensions; we might build a symbolic display along these lines (Fig. 83). The three degrees of

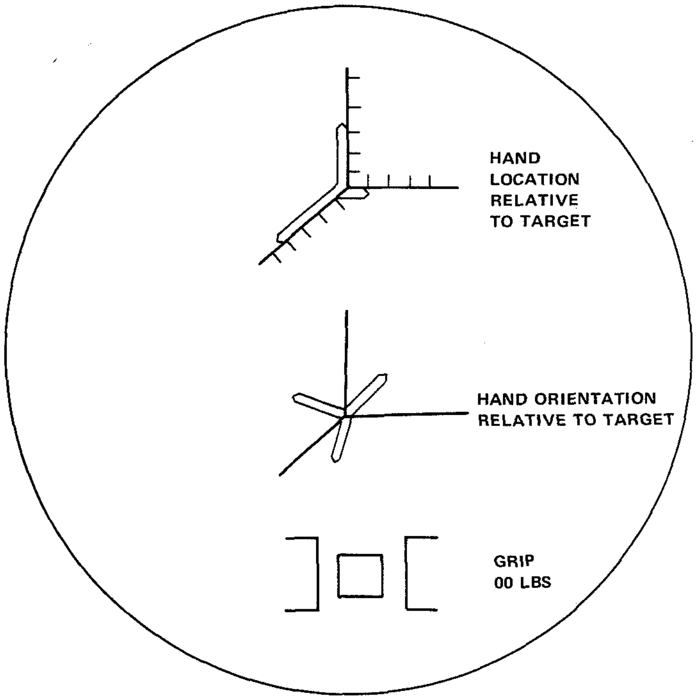


Figure 83 *A possible abstract visual display indicating the status or configuration of a seven-degree-of-freedom teleoperator.*

freedom representing the position of the hand relative to the target could be portrayed on a CRT-drawn set of Cartesian axes. Similarly, the hand orientation—three more degrees of freedom—could be displayed as a vector relative to the orientation of the object. Finally, hand closure around the target, the seventh degree of freedom, could be represented by a vise-like sketch. The grip in pounds could be displayed numerically next to the grip display.

Why would one want to employ symbolic or abstract displays instead of honest, natural pictorial displays?

1. The natural visual display may possess noise, distortion, and bad contrast. Signal processing can clean it up.
2. A natural visual display requires an immense quantity of information—a large bandwidth. Symbolic and abstract displays can be drawn with far less bandwidth. On a lunar spacecraft, for example, signal processing equipment can eliminate all data in the natural scene except those pertaining to the targets and the teleoperator configuration.
3. In some instances, there is no natural visual display because natural and artificial lighting are absent.

4. Symbolic and abstract displays may lead to better performance of teleoperators. (A contentious statement.)

An extreme example of abstract, symbolic displays is the teletypewriter employed in supervisory control. An output device as well as an input device, the teletypewriter can print out manipulator configuration coordinates, the geometric relationship of the targets, and status data—in fact, anything we wish to know about the teleoperator and its task. Of course, there is no anthropomorphism in the printout of a teletypewriter; it is hard to imagine how an operator might identify himself with the task. Operation would certainly not be natural in the sense of everyday experience. Some people, however, identify well with symbols and mathematical relationships. A matrix is as real to them as an actual force on the target. Manipulation in this case would be much like playing chess without a chessboard—some people can do it.

The hardware available and under development for the display of abstract and symbolic information, like the television systems used for natural visual displays, is beyond the scope of the survey. The variety of media is large and gives the teleoperator designer ample opportunity to explore new modes of machine-to-man communication. We list some types of visual displays:

Thermochromic	Photochromic
Fluidic	Magnetic
Electrostatic	Laser
Plasma	Electroluminescent

Reference 97 surveys the state of the art for these types. The more conventional CRT and projected large-screen displays are discussed in Refs. 98 and 99.

Some of the experimental displays under development for submarines are similar to the displays we might expect in a teleoperator. McLane and Wolf have summarized some of the Navy's symbolic display work.[100] In Fig. 84, a type of symbolic depth-azimuth display is portrayed. Note that sonar supplies the basic environmental information; this is codified into abstract symbols representing obstacles and targets. The depth and azimuth scales allow the operator to avoid obstacles and, perhaps, torpedoes. Ship status is also indicated. Horizontal range to the target is not given on this display, but it could be indicated numerically on the scope face. Another type of symbolic visual display is shown in Fig. 85. On this the ship's attitude is portrayed geometrically and distance to the target or obstacle can be judged from the perspective present in the display. Depth relative to the target is also intrinsic in the display. One can imagine displays similar to these drawn for a manipulatory situation—Fig. 82 could be redrawn with perspective and other types of coding added. The geometrical cues relating ship to obstacle are analogous to those relating a manipulator arm to a target.

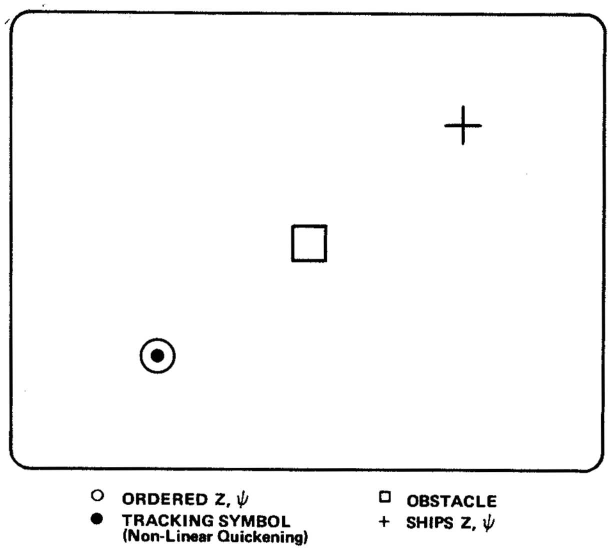


Figure 84 *A possible type of symbolic visual display showing a submarine's depth-azimuth relationship to an external target. The target and relative configuration of a teleoperator could be indicated by a similar display.*[100]

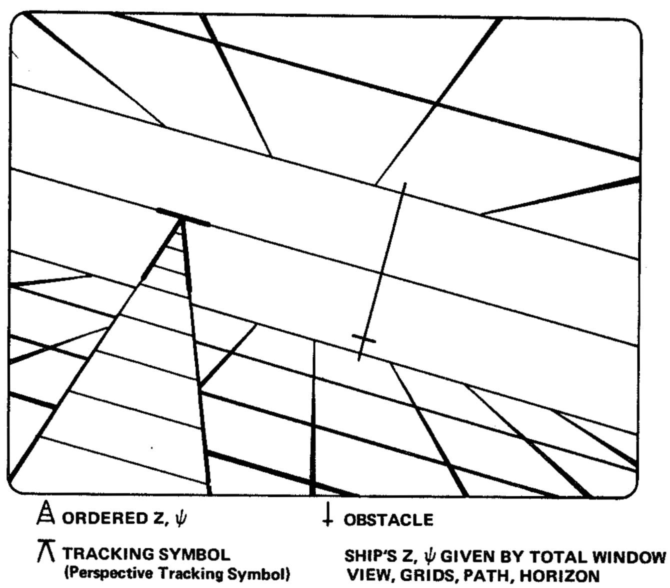


Figure 85 *A possible type of abstract visual display indicating a submarine's attitude and relationship to an external target.*[100]

One type of abstract visual display that has been developed in connection with teleoperator technology is the M.I.T. tactual sensor. One version of this sensor was described in Ref. 1. A later model is pictured in Fig. 86. Touch in this sensor is detected as a distortion of a flexible surface, which is then imaged upon a fiber-optics bundle and ultimately on a CRT. We have in effect an abstract visual display of touch as "felt" by the manipulator jaws (Fig. 87). Despite the fact that there is some correlation between the shape of an object and the pattern viewed on the CRT, correct and facile pattern interpretation requires operator training and may divert him from the task.

VISUAL PREDICTOR DISPLAYS

Displays which help the operator predict the future are helpful in dynamic situations, such as high-speed piloted aircraft and submarines. Manipulators ordinarily move so slowly that predictor displays are of little importance. The major exception occurs where significant time delay exists. (See Chap. 3 for the effects of time delay.) In cislunar space, on the Moon,

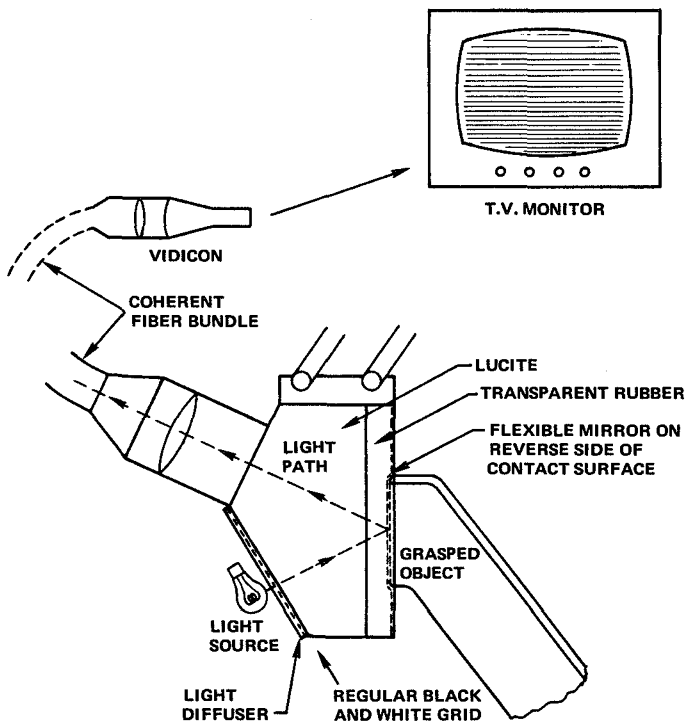


Figure 86 *Schematic of the M.I.T. optical touch sensor. See Fig. 87 for typical displays.*[13]

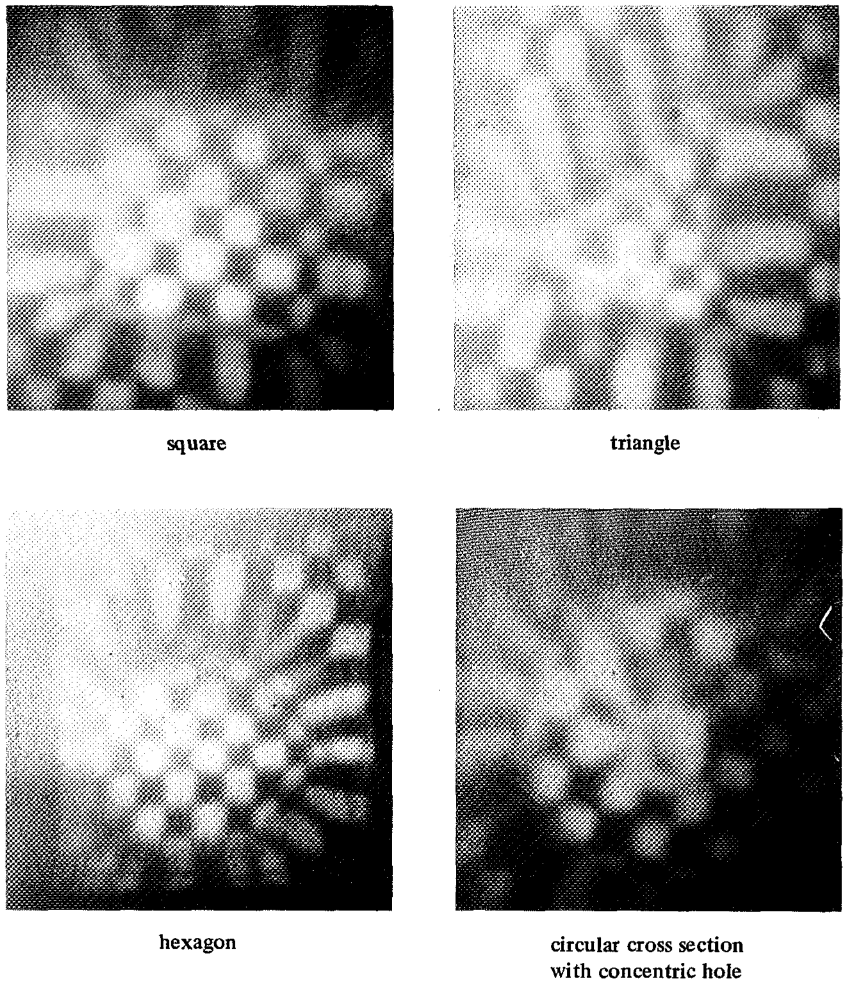


Figure 87 *CRT displays showing the effects of various shapes on the M.I.T. tactual sensor. (Courtesy of T. B. Sheridan, M.I.T.)*

and beyond, teleoperator performance can be enhanced if the operator back on Earth has some sort of predictor display that estimates the consequences of his actions before he issues commands to the Earth-based transmitter.

Predictor instruments look ahead in time by constructing "models" of the situation—primarily models of the machine and its environment. The model, possibly an electrical analog, is then run faster than real time (that is, ahead of real time) and its performance is displayed for the operator. In many human tasks, a person performs these computations in his head intuitively. In guiding an automobile around a curve, the driver projects his vehicle's position as a function of time for various combinations of control actions.

The model of the situation employed by a predictor instrument is usually displayed visually. However, there is no reason why force and tactual feedback cannot be predicted for the operator. In fact, if predicted force feedback could be added to predicted visual feedback on the same time scale, the operator would have excellent grounds for decision-making.

A visual predictor display must be abstract or symbolic because there is no knowledge of the real natural world of the future—only projections. It is customary, however, to display projections in time in anthropomorphic fashion, say, as a projected vehicle track on the actual televised scene.

Aircraft instrument panels have long utilized time-derivative (rate of change) data in helping the pilot maneuver his craft.* Ziebolz and Paynter discussed the possibility of improving upon simple derivative information by employing fast models or analogs of the entire system.[26] In the early 1960s, Kelley and his associates developed a Predictor Instrument for the Navy to help control submarines.[101,102] These ideas form the basis for teleoperator predictor displays.

Because of its historical importance, we sketch a few details of Kelley's Predictor Instrument. Figure 88 shows the block diagram for this device. The heart of the Predictor Instrument is a miniature computer (an analog computer in this case) that models the system. As the sensors feed in information about the present, it predicts the future for various "degrees of freedom" (Fig. 89). The operator "sees" the future as a function of time and takes whatever action seems appropriate. The original purpose of the Predictor Instrument was not to overcome signal transmission time delay but rather to offset the operator's reaction time and warn him of future consequences that he might not anticipate from real-time data alone.

NASA and the Air Force have investigated predictor displays for use in orbital rendezvous, an operation where terrestrial vehicle experience is not too helpful.[103-105] These studies employ fast-time models for prediction; again the objective is to help the operator in a complex real-time situation. Air Force-sponsored simulator studies confirm that a predictor display materially helps the astronaut.

More germane to the teleoperator time-delay problem in outer space are the studies of predictor displays for lunar vehicles. Dunlap and Associates, Stanford University, General Motors Corp. and others have completed studies and simulation experiments.[21,106] Again, a fast-time model of the physical system constitutes the basis for prediction.

The studies proposed superimposing a symbolic track representing the predicted vehicle motion upon a symbolic or pictorial display of the lunar environment (Fig. 90). It should be emphasized that these proposed displays are the results of studies and that no hardware exists at the present time.

*The use of derivative information in generating displays is termed "quickening" and the quickened display is often called "augmented."

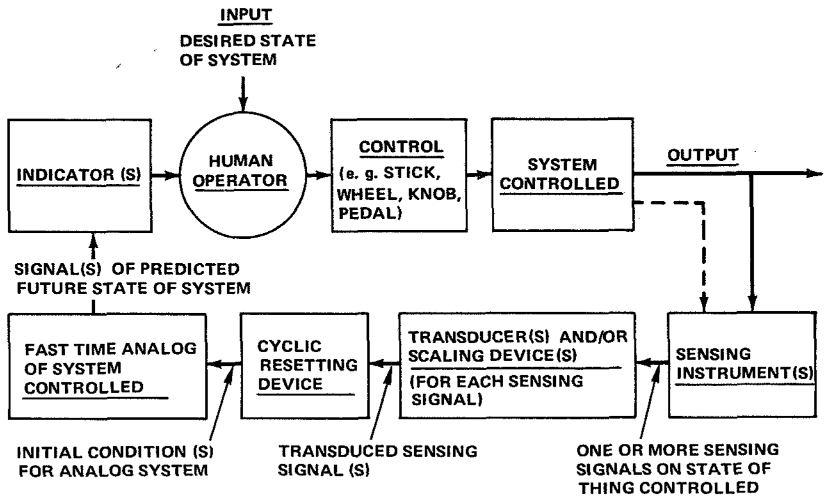


Figure 88 *General block diagram of the Predictor Instrument. (Courtesy of C. R. Kelley, Dunlap and Associates.)*

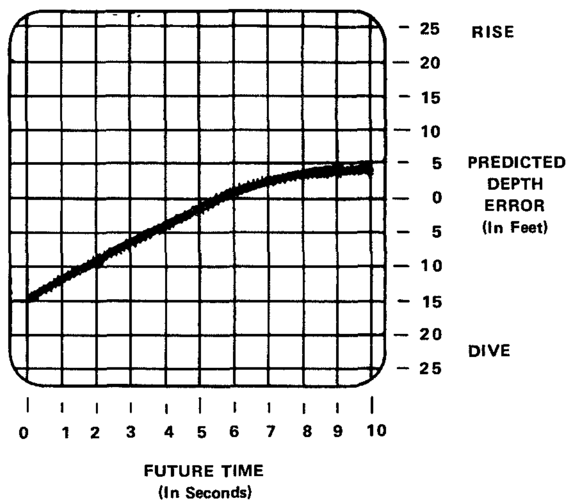


Figure 89 *The Predictor Instrument developed by Kelley and colleagues at Dunlap and Associates, gives the operator a preview of the future using a fast model of the physical system. This particular display forecasts depth of a submarine.*

Leslie et al.[22] have carried out simulator studies of the effectiveness of predictor displays in the operation of lunar roving vehicles. Their results indicate that the deterioration of performance due to time delay can be all but erased through the use of a predictor display.

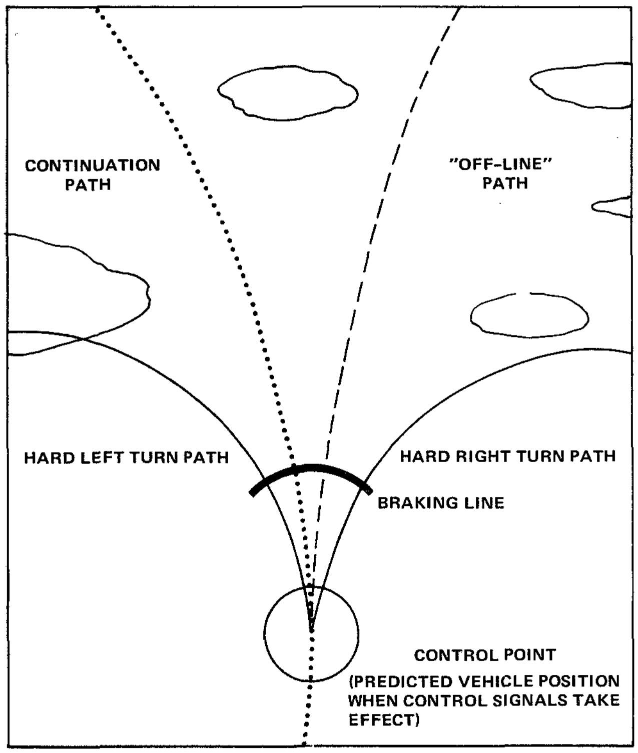


Figure 90 *A possible type of predictor display for a lunar roving vehicle.*

The only teleoperators to operate under time-delay restrictions to date have been the Surveyor surface samplers (see Chap. 5). Operations with the surface sampler were slow and deliberate and made use of the move-and-wait strategy. The primary display aiding surface-sampler manipulation of the lunar soil was pictorial, using the pictures taken by the Surveyor vidicon camera. Because of the 1.3-second signal-propagation time delay and the time required to scan and transmit the vidicon image, the display was what we might call "historical" in nature. Each picture was several seconds old at best. The operator of the sampler could, of course, examine as many of these still photos as he wished, but they gave him little identification with the dynamics of the experiments.

Movies made after the mission from successive Surveyor pictures have added real-time dynamic insight to the sampler operations. By showing several hour's pictures in a few seconds, the motion of the sampler and soil movement can be seen. In effect, the human brain melds the time-separated photos into a smooth whole. In future lunar operations, sped-up historical displays may quickly recapitulate the last hour of motion to lend reality to the present scene. In planning his next move, the operator could command this review of past operations at will; his brain could then project consequences of his actions better. Time delay is not eliminated, of course, but time seems compressed to terrestrial scale and the operator can use his worldly experience to predict what might happen for each prospective command.

FORCE FEEDBACK AND TACTUAL DISPLAYS

Next to vision, force feedback to the hands, arms, or legs of a teleoperator is the most important type of "displayed" information. The mechanical and electromechanical bases for force feedback were sketched earlier in this book and in Ref. 1. Cables and servo motors force slave arms to follow master arms and vice versa when the slave arm encounters an object. The "display," of course, is the totality of forces and pressures applied to the hands, arms, and legs of the operator.

In tactual (or tactile) feedback, the situation is complicated by the fact that a well-defined, two-dimensional field of pressure stimuli is desired. Touch feedback devices thus take on some of the features of visual displays. As mentioned earlier, some tactual displays are actually visual in character. Here, we deal only with those displays that stimulate the surfaces of the fingers, although it might be argued that vibrator alarms, such as those associated with artificial limbs (see Chap. 5) might also be considered useful tactual displays for teleoperators.

Bliss and his colleagues at Stanford Research Institute (S.R.I.) have developed tactual displays for a wide variety of potential applications.[107,108] Bliss' group has constructed reading machines for the blind which convert printed letters into tactual displays that can be read by the fingers. If the fingers can discern the shapes of the letters from a tactual display, the same displays could give an operator a good sense of feel in remote manipulation.

Bliss and his associates have worked with electromechanical, piezoelectric, electrical, and air-jet stimulators. The air-jet stimulators have proven successful and have been employed in many S.R.I. experiments (Fig. 91). Airjet stimulators arrayed 12 x 12 have been built finger-tip size—this is the array that resolves letters of the alphabet. One can conceive of such arrays being built into the master hand controls of advanced master-slaves, with each of the 144 stimulators actuated by a corresponding pressure-sensitive spot (perhaps a piezoelectric crystal) on the slave hand.

How useful would tactual displays be if visual displays and force feedback were already applied to a given problem? Intuitively, one would say tactual feedback must be beneficial; but no one knows for sure. Bliss' human factors studies with tactual arrays have indicated that the human delay time with tactual displays alone is appreciably longer than for an equivalent visual display alone. However, human reaction time when visual and tactual displays

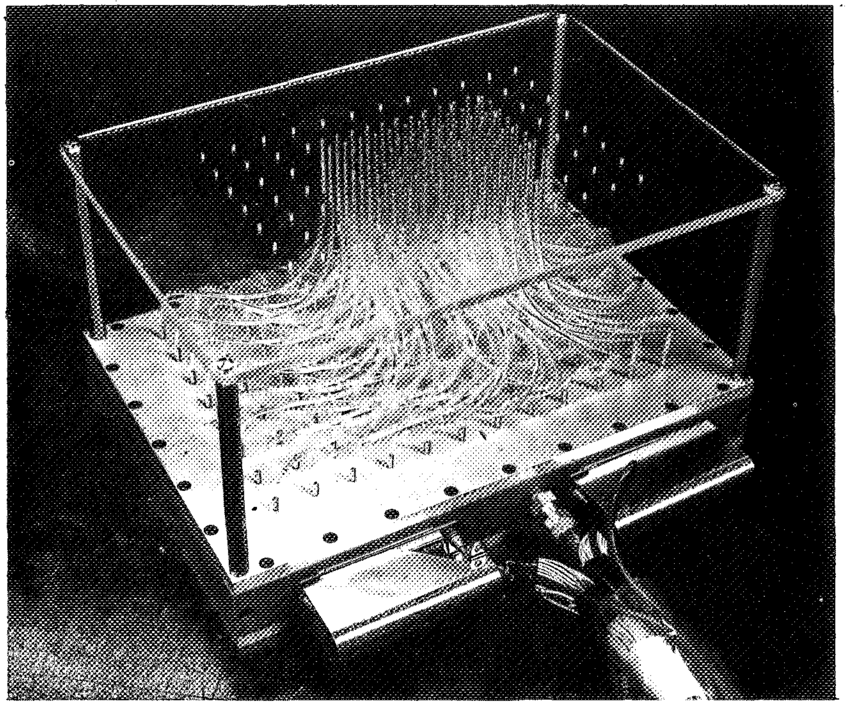


Figure 91 *A 12 × 8 array of air-jet tactual stimulators. The active area of the array is finger-tip size. (Courtesy J. C. Bliss, Stanford Research Institute.)*

are used simultaneously is shorter than for either display alone. Some manipulatory experiments will have to be made to determine the true utility of tactual displays. Any performance advantages would have to be weighed against the increased complexity of the teleoperator system and the engineering difficulty of installing the sensors and stimulators on machine and man.

Chapter 7

CONTRIBUTIONS FROM TELEOPERATOR CONTROL TECHNOLOGY

Teleoperator control technology is young compared to the experience we have amassed in the manual control of aircraft and other vehicles. Mostly, the flow of control technology has been into rather than out of the teleoperator field. Servos, joystick controls, and computer software came well-developed and were integrated early into teleoperator technology essentially as is. Despite their relative youth, teleoperators have contributed some significant theory and hardware developments that will eventually find applications elsewhere in our technological repertoire. Below, we tabulate these key contributions.* First the important theoretical developments.

Contribution	Possible Applications to Other Areas
Teleoperator state theory (M.I.T., U.C.L.A.)	Automated factories, robots, almost any machine
Human factors studies of man and teleoperator and the effectiveness of displays (U.C.L.A., Electric Boat, Stanford Research Institute (S.R.I.), U.S.A.F. (Wright Field)	Better understanding of man-machine relationship useful in the design of all manually controlled machines
Studies of the effects of time delay (M.I.T., Stanford University)	Applicable to the operation of all very remote machines (planetary probes, automated life-detection laboratories)
Development of a rationale for supervisory control (M.I.T.)	All manually controlled machines use these concepts (aircraft, submarines, etc.)
Programs and software for computer-controlled manipulators (M.I.T., Case)	Almost any man-machine combination, (automated factories, robots, aircraft)

*See Ref. 1, Chap. 2, for a thorough review of teleoperator applications. Only specific contributions from teleoperator control technology are covered here.

Computer-assisted adaptively controlled machines (S.R.I., M.I.T.)	Automated factories and robots
Multijoint servo theory (GE)	All servoed machinery

In addition to the above theoretical developments, some important pieces of teleoperator hardware have been built that may have application in other areas.

Contribution	**Possible Application to Other Areas**
The ANL E4A electric master-slave	This control technology could be used in other remote-control applications (undersea mining, spacecraft control, unmanned weather stations, etc.)
The ANL head-controlled TV display	All remote operations whether teleoperators are employed or not. (Remote surveillance and exploration)
Tactual displays (S.R.I., M.I.T.)	In aids for the blind, possibly in oil-well work and deep sea exploration where a sense of touch is helpful in installing equipment and instruments
The GE Walking Truck and Hardiman	The electrohydraulic and high-power electric servos developed here and their controls should also be useful in earth-moving equipment, mining machinery, etc.

Summarizing, developments in teleoperator control are helping significantly in the automation of many human tasks and the successful bridging of man-machine interfaces. These are two distinctly different areas. The first brings to mind visions of highly automated factories and household robots. This sort of machinery is nearly fully automatic and cannot be classified with teleoperators; however, teleoperator control, particularly computer-aided supervisory control, is definitely oriented in the direction of automatic control. Teleoperator control is philosophically somewhere between the disciplines of manual control and automatic control; and it draws from and contributes to each. The second important application area—bridging the man-machine interface—includes all man-machine systems and in the modern world, this means everything from computers to spacecraft to the telephone system. All advances in teleoperator control technology enhance our ability to weld man successfully with other kinds of machines.

In teleoperator control, we stretch man to make him more like a machine; viz., nonanthropomorphic control. We also mould machines so they are more like men; viz., exoskeletons, artificial limbs, and manipulators. It is because teleoperators help hybridize man and machine that they are so important to our basic technology.

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