GPO PRICE $ ____________

CFSTI PRICE(S) $ ____________

Hard copy (HC) 3.00

Microfiche (MF) .65

ff 653 July 65

NASA SP-5047

AN AEC-NASA TECHNOLOGY SURVEY

TELEOPERATORS AND HUMAN AUGMENTATION

FACILITY FORM 602

N68-18870
(ACCESSION NUMBER)

(THRU)

273
(PAGES)

1
(CODE)

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(NASA CR OR TMX OR AD NUMBER)

05
(CATEGORY)

ATOMIC ENERGY COMMISSION
UNITED STATES OF AMERICA

TECHNOLOGY UTILIZATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA SP-5047

TELEOPERATORS AND HUMAN AUGMENTATION

An AEC-NASA TECHNOLOGY SURVEY

By
Edwin G. Johnsen
and
William R. Corliss

Prepared under contract for the
NASA Office of Technology Utilization

Washington, D.C. December, 1967

For Sale by the Superintendent of Documents,
U.S. Government Printing Office, Washington, D. C. 20402
Price $1
Library of Congress Catalog Card Number 67-62098

Foreword

This book describes general purpose, dexterous, cybernetic machines developed in the last 25 years. The Atomic Energy Commission and the National Aeronautics and Space Administration have accelerated the development of such "teleoperators."

Teleoperators can both extend and amplify human beings' capabilities. Indeed, the basic concepts and the same techniques now used in nuclear and space work can be adapted for use in exploring the seas, increasing industry's productivity, and aiding physically handicapped persons.

These machines are now enabling men to manipulate materials in hazardous environments safely. The prior existence of many techniques in this field has made the progress in the nuclear rocket program possible and that program, in turn, is contributing to advances in the technology.

While automation has become a major force in the economic development of nations, many operations will continue to require human judgment and adaptations to unknowns. Such systems in combination with teleoperator systems may free men further from dull, routine tasks for more rewarding and satisfying activities.

Teleoperators need not always be anthropomorphic, but many of the insights and devices resulting from study of these fascinating machines may help men surmount handicaps to their survival in familiar as well as in distant and less favorable environments.

The authors have emphasized the principal subsystems of contemporary teleoperators in this survey of recent developments and trends. Their purpose has been that of the NASA Office of Technology Utilization: To increase the dividends to mankind from space age technology. Some of their observations may seem naive to readers a generation hence, but the design principles set forth still will be valid.

MILTON KLEIN, *Manager,*
AEC-NASA Nuclear Propulsion Office

GEORGE J. HOWICK, *Director,*
Technology Utilization Division, NASA

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Acknowledgments

Teleoperator technology has germinated and grown independently wherever man has tried to augment his hands, arms, and legs with machines. Literature and knowledge are dispersed among the nuclear, space, undersea, medical, and several other areas of technical activity. The authors wish to acknowledge the help of the following individuals in obtaining and checking basic information:

David C. Cramblit, Marshall Space Flight Center
Ray Goertz, Argonne National Laboratory
Alexander Levin, U.S. Army Engineer Research and Development Laboratories
Donald F. Melton, Programmed and Remote Systems Corp.
Don Mingesz, Argonne National Laboratory
Eugene F. Murphy, Veterans Administration
Frank Ranahan, Holmes & Narver, Inc.
Andrew B. Rechnitzer, Ocean Systems Operation, North American Aviation, Inc.
James B. Reswick, Case Institute of Technology
Samuel Snyder, NASA Headquarters
A. Bennett Wilson, Jr., National Research Council

Many other individuals helped materially during the research phase of this survey, and we extend our thanks to them, too:

Lowell A. Anderson, NASA Headquarters
Victor C. Anderson, Scripps Institution of Oceanography
George Anton, NASA, NRDS, Nevada
Norman Belasco, Manned Spacecraft Center
A. George Berbert, Jr., Richie, Inc.
Philip Bolger, NASA Headquarters
William E. Bradley, Institute for Defense Analyses
E. Burciaga, NASA West Coast Operations Office
Frank Chesley, Central Research Laboratories
Billy M. Crawford, Wright-Patterson Air Force Base

Jack Cully, AEC, Albuquerque Operations Office
Stanley Deutsch, NASA Headquarters
R. L. Drexler, General Electric Co.
Albert B. Driscoll, Central Research Laboratories
M. J. Feldman, Argonne National Laboratory (Idaho)
William R. Ferrell, M.I.T.
James B. Griffin, Ling-Temco-Vought
Quentin Hartwig, George Washington University
William G. Houck, U.S. Navy
Rim Kaminskas, Giannini Controls
R. S. Karinen, Programmed and Remote Systems Corp.
George Kovatch, NASA Electronics Research Center
Fred Leonard, Walter Reed Army Medical Center
R. A. Liston, U.S. Army, ATAC
Paul Littenecker, AEC, Idaho Falls
John Lyman, University of California, Los Angeles
John C. McKinley, AEC, Idaho Falls
John Merchant, Honeywell, Inc.
Harry Mergler, Case Institute of Technology
John Morfitt, General Electric Co.
R. A. Morrison, Space-General Corp.
Ralph S. Mosher, General Electric Co.
K. G. Richardson, Electric Boat Division, General Dynamics
Steven Roffis, American Machine and Foundry
Earl R. Schlissler, Westinghouse Electric Corp.
John Schulte, Los Alamos Scientific Laboratory
Thomas B. Sheridan, M.I.T.
Dan Spadone, U.S. Navy
L. G. Stang, Jr., Brookhaven National Laboratory
Warren H. Straly, Serendipity Associates
Allyn Vines, Woods Hole Oceanographic Institute
Charles E. Vivian, Lockheed Missiles and Space Co.
G. von Tiesenhausen, Marshall Space Flight Center
Robert Warner, Los Alamos Scientific Laboratory
Robert Wiesner, Los Alamos Scientific Laboratory
Kent Wilson, Ocean Systems Operation, North American Aviation, Inc.
H. F. Wuenscher, Marshall Space Flight Center

CHAPTER 1

Introduction to Teleoperators

Early in the Nineteenth Century, Napoleon sat across a chessboard from a ferocious-looking automaton swathed in the robes of a Turk. Napoleon moved his chessmen into battle; the Turk did the same. Then, when Napoleon blundered three times in succession, the audacious machine swept the board clean with an iron hand.

The chess-playing Turk was constructed by Baron Von Kempelen; it took on all comers until Edgar Allen Poe deduced that beneath the Turk's chess table there was a midget chess expert who manipulated the various controls that gave "life" to the machine. Those were the innocent times when man believed that he could build anything—not the least of which was a chess-playing robot.

Now that man must work in outer space, ocean depths, and other hazardous environments, he is building machines that recall Von Kempelen's intricate "automaton." These machines perform as appendages of man, particularly his arms, hands, and legs. Radio links, copper wires, and steel cables replace nerve fibers and muscle tendons. We shall call these man-machine systems "teleoperators," whether they are the tongs used by the old-fashioned grocer to retrieve a cereal box from the top shelf or the mechanical hand that may repair some future nuclear-powered space vehicle. The basic concept is portrayed in fig. 1, where man's bodily dexterity is shown communicated across a barrier to mechanical actuators that can operate under loads too great for an unaided man, or in an environment too hostile or too far away for him to conquer in person. A teleoperator augments a normal man, or, in the case of prosthetics, helps a handicapped man become more nearly normal.

NASA is concerned with the development of teleoperators because many astronautical targets are so far away that they must be explored by proxy. Yet the amplification and extension of man via the teleoperator concept transcends space exploration. A survey of this fascinating technology must also embrace many advances made in the nuclear industry, in undersea exploration, in medicine, and in the engineering of "man amplifiers."

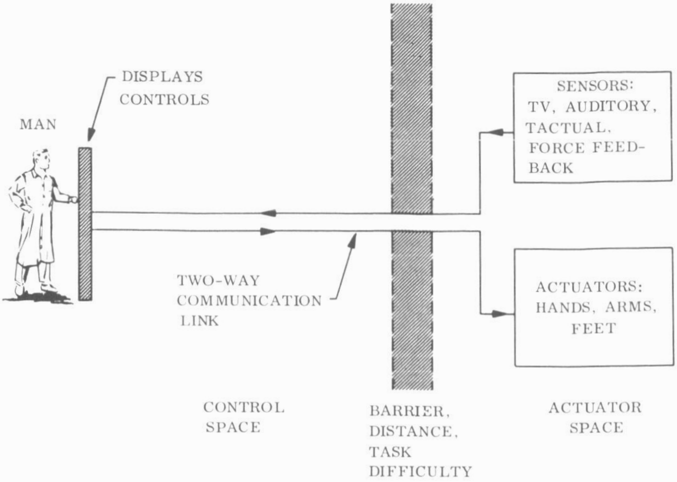

FIGURE 1.—Generalized schematic of a teleoperator incorporating dexterous actuators in the actuator space. The "barrier" between the control and operating spaces may result from distance, a hostile environment, or the sheer physical magnitude (weight, for example) of the task to be done.

A teleoperator is a *general purpose, dexterous, cybernetic machine*. These adjectives separate teleoperators from other machines. The adjective "cybernetic" excludes all preprogrammed machinery, such as timer-controlled ovens, record-changing phonographs, and much of the machinery on automatic production lines. A teleoperator, in contrast, *always* has man in the control loop. The other adjectives—"dexterous" and "general purpose"—sharpen the focus further. These semantic sieves trap human-controlled, but undexterous, machines such as remotely controlled aircraft and telephone switching circuits. The man-machine systems that fall through our sieves allow man to:

—Pick up and examine samples of the lunar surface while remaining on Earth.
—Repair an underwater oil pipeline from a surface ship.
—Manipulate radioactive nuclear fuel elements in a hot cell.
—Regain dexterity with an artificial limb (the prosthetics concept).
—Lift a ton-sized load (the man-amplifier concept).

The prefix "tele" in teleoperator describes the ability of this class of man-machine systems to project man's innate dexterity not only across distance but through *physical barriers as well.*

When an area of technology with latent commercial potential approaches that point where exponential growth appears imminent, engineers invariably become word testers. Because no unified discipline welds the technical innovators together, synonyms and overlapping words proliferate. The following glossary should dispel some of the confusion:

> *Telepuppet.* A word coined in the 1950's by Fred L. Whipple, now director of the Smithsonian Astrophysical Obeservatory, to describe his concept of how sophisticated machines could take the place of man on spacecraft. The word has not become popular, presumably because "puppet" implies toys and entertainment rather than science and engineering.
>
> *Telechirics.* John W. Clark synthesized this word from Greek roots while at Battelle Memorial Institute in the early 1960's (ref. 1). Literally, telechirics means "remote fingers." It is descriptive, but unfortunately excludes walking machines and man amplifiers.
>
> *Telefactor.* The idea of making or doing something at a distance is intrinsic in this word conceived by William E. Bradley, at the Institute for Defense Analyses (ref. 2). It is semantically sound, but many people do not immediately recall that "factor" implies doing or making as well as algebra.
>
> *Cybernetic anthropomorphic mechanism* (*CAM* for short). Ralph S. Mosher, at General Electric, has often used this term in his papers on walking machines (ref. 3), but it excludes many nonanthropomorphic mechanisms included in this survey. Mosher now refers to the field as *mechanism cybernetics,* a term that omits only the desired attributes of dexterity and versatility.
>
> *Master-slave.* Originated by Ray C. Goertz at the AEC's Argonne National Laboratory in the late 1940's, this term is generally applied only to the common mechanical and electronic manipulators that have long been used in hot cells (ref. 4).

The terms "manipulator" and "remote control" are also often associated with the telemechanism field. The first term is too narrow a concept, since it excludes walking machines and exoskeletons. "Remote control" is too broad because it includes everything man does at a distance, even to changing a TV channel from his armchair.

A compact, accurate synonym for general purpose, dexterous, cybernetic machines may evolve as the field matures. Meanwhile, "teleoperator" will serve in this book.

Figure 2 rounds out the picture of the teleoperator by portraying its full set of subsystems (ref. 5). Four of the nine subsystems deal directly with machine augmentation of man. These four are:

—*The actuator subsystem* that carries out the manipulations and other dexterous activities ordered by the human operator. The actuators may be stronger, more dexterous, and faster than the operator.

—*The sensor subsystem* that permits the operator to see, feel, hear, and otherwise sense what the actuators are doing in the actuator space and what their environment is.

—*The control subsystem,* which includes the human operator, analyzes information fed back by the sensors in the actuator space and compares this with the operational objectives. The result is a series of commands to the actuator subsystem.

—*The communication subsystem* is the information hub of the teleoperator. It transmits commands and feedback among the various subsystems.

The supporting roles of the other five subsystems shown in fig. 2 are apparent from their names. Chapter 3 will elaborate on the parts played by the nine subsystems and describe how they act in concert to carry out man's directives.

While the system diagram may seem somewhat involved, it is sufficiently general to include simple tongs for handling radioactive samples and extremely complex systems.

RECENT HISTORY

The chess-playing Turk was preceded by the marvelous automatons of the Jaquet-Droz father-son team in the late 1700's (ref. 6). Controlled by grooved, rotating disks, the Jaquet-Droz automatons could play music and write out compositions; one in particular, "The Draughtsman," astounded King George III and Queen Charlotte by sketching them on the spot—or so it seemed. (Such a machine would be called preprogrammed today.) A "Steam Man," built by a Canadian, Professor George Moore, in the 1890's, was powered by a half-horsepower, high-speed steam engine; this primitive walking machine could puff along pulling light loads behind it. The Westinghouse automatons exhibited at the New York World's Fair in 1939, "Elektro" and "Sparko" (fig. 3), could walk, talk, and distinguish colors. The word "robot" means "worker" in Czech and gained popularity from Karel Capek's 1923 play "R.U.R." (for "Rossum's Universal Robots").

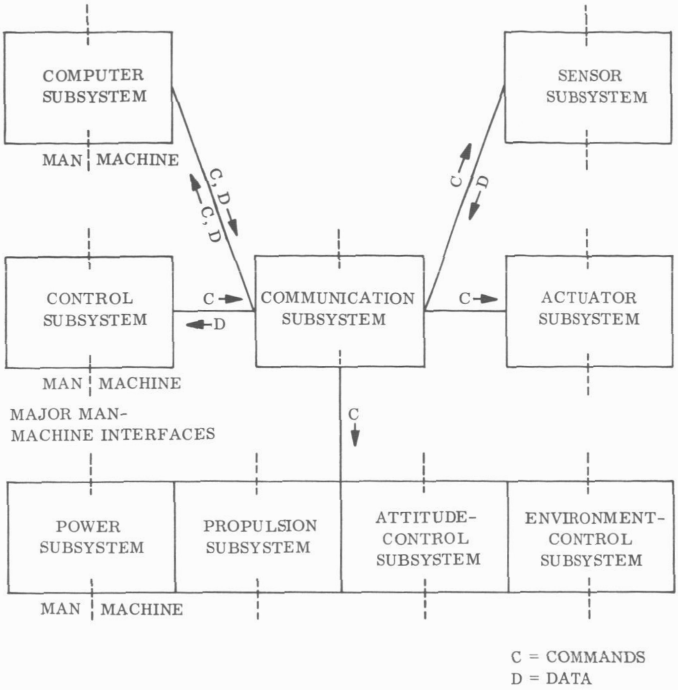

FIGURE 2.—Schematic of a general purpose, dexterous, cybernetic teleoperator, showing the nine subsystems. A man-machine interface may be created in any of the subsystems.

Today a robot is generally considered to be an automaton made in the shape of a man. Robots are usually preprogrammed or, in science fiction particularly, self-adapting and intelligent, not requiring and even disdaining help from humans. In contrast to robots, man is always intimately in the loop in the teleoperators discussed in this book.

Taking the historical road labeled "teleoperators," let us pass over the early and well-documented developments of television, cybernetics a la Norbert Wiener, radio control, and the supporting technology of prosthetics, and begin with master-slave manipulators built under the impetus of the atomic energy program. These were the first really sophisticated machines to project man's manipulative capability into a hazardous environment.

The chronology runs like this:

—*1947*. Mechanically and electrically connected unilateral*

---

*"Unilateral" means that there is no kinesthetic or force feedback as there is in a "bilateral" system. See table 3 for definitions of the various kinds of teleoperators.

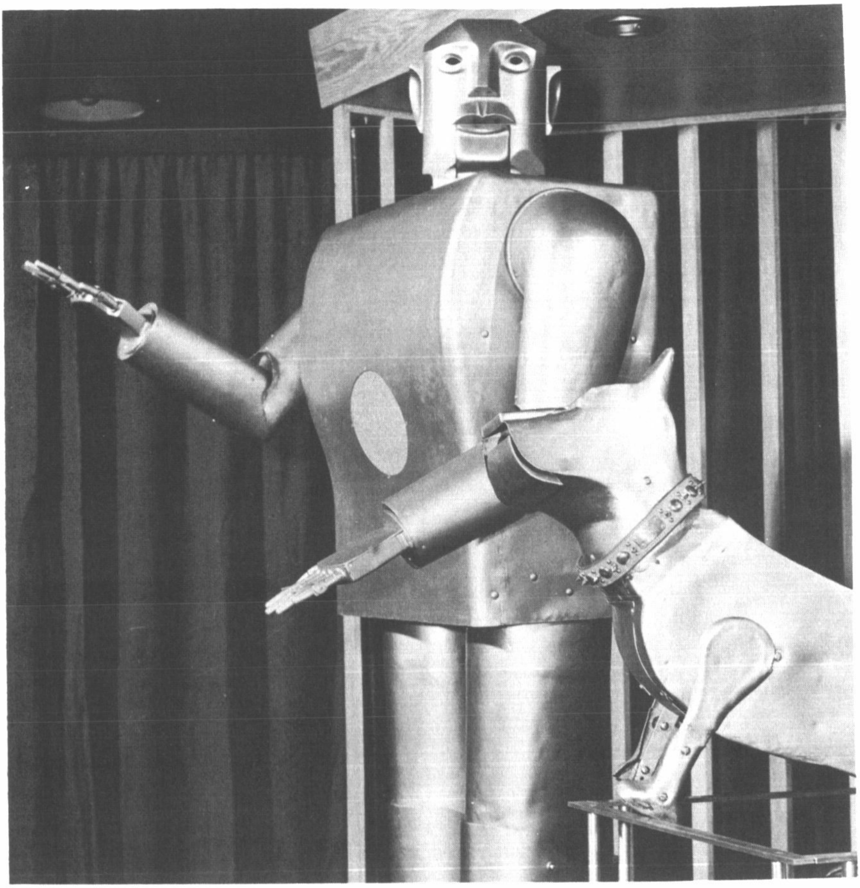

FIGURE 3.—"Elektro" and "Sparko," automatons shown at the 1939 New York World's Fair. (Courtesy of Westinghouse Electric Corp.)

manipulators were developed at the AEC's Argonne National Laboratory (ANL).

—*1948.* Ray Goertz and his coworkers at ANL developed the Model-1 bilateral mechanical master-slave manipulator (fig. 4) (ref. 7).

—*1948.* John Payne built a mechanical master-slave manipulator at General Electric (ref. 8) and many AEC installations subsequently acquired a great variety of mechanical manipulators (fig. 5).

—*1948.* General Mills produced the Model-A unilateral manipulator in which the arms and hands were driven by switch-controlled motors rather than by direct mechanical

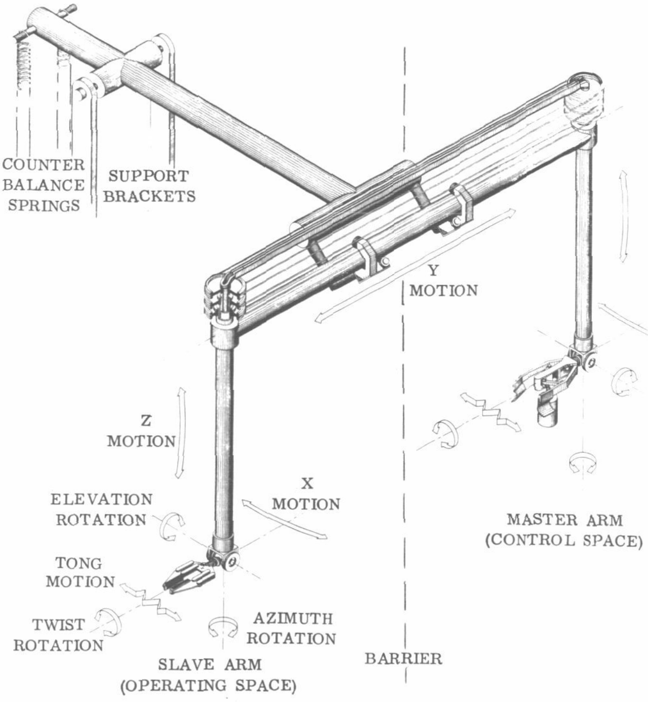

FIGURE 4.—The ANL Model–1 experimental mechanical master-slave manipulator. Motions of the master arm are mechanically communicated to the slave arm. Because the reverse is also true, this is termed a "bilateral" manipulator. (Courtesy of Argonne National Laboratory.)

or electrical linkage to the operator (as in the true master-slave). The Model-A became a "workhorse" of the nuclear industry in tasks requiring more strength and working volume than possible with master-slaves.

—*1950.* ANL experimented with master-slaves coupled with stereo TV.

—*1954.* Development of the Argonne Model-8 mechanical master-slave manipulator was completed. This manipulator is still predominant in the atomic energy industry and is manufactured commercially.

—*1954.* Ray Goertz built an electric master-slave manipulator incorporating servos and force reflection (sense of touch or "feel") (fig. 6) (ref. 5). The master-slave position control of the manipulator arms and hands plus force reflection made this the first bilateral electric manipulator.

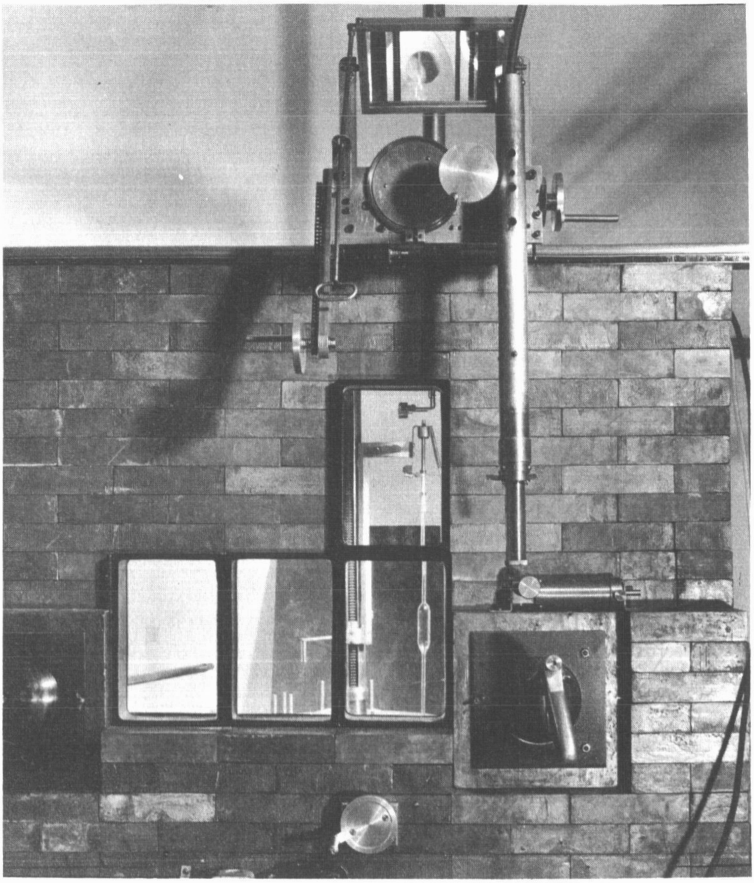

FIGURE 5.—An early manipulator at Brookhaven National Laboratory. Motion was communicated over a lead-brick wall by various mechanical linkages. Note mirrors in viewing scheme. (Courtesy of L. G. Stang, Jr., Brookhaven National Laboratory.)

—*1954*. The GPR (General Purpose Robot) was built at the AEC's Savannah River Plant. This was the first, general purpose manipulator-equipped vehicle.

—*1957*. Professor Joseph E. Shigley, at the University of Michigan, built a primitive walking machine for the U.S. Army (ref. 9). Although many walking machines were built earlier, Shigley's inaugurated the present-day Army program in "off-road" locomotion.

—*1958*. First mobile manipulator with TV was built at ANL. This teleoperator was called a "slave robot."

—*1958*. Ralph S. Mosher and coworkers at General Electric

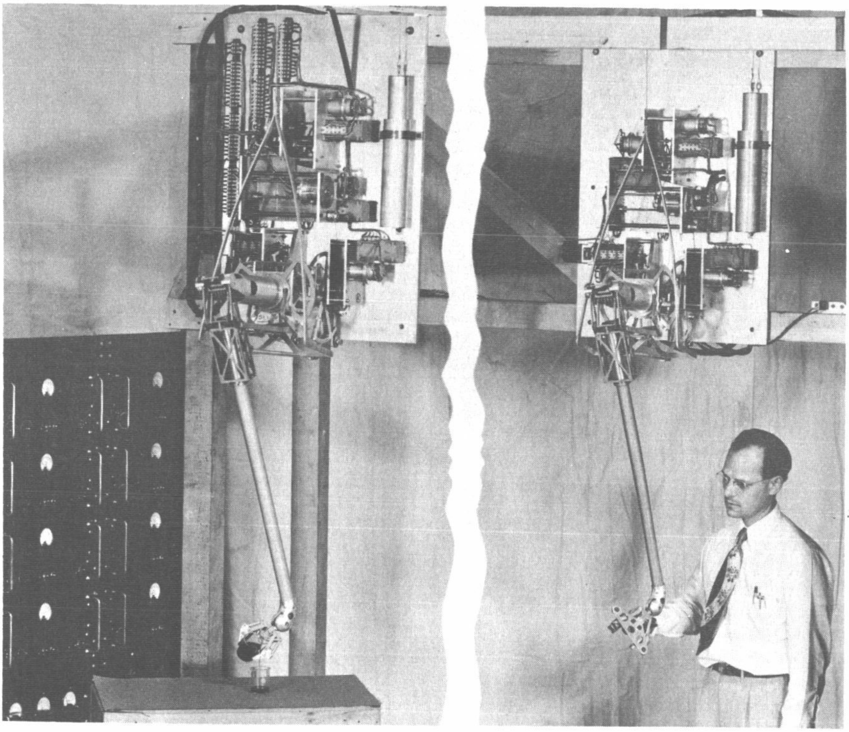

FIGURE 6.—The ANL Model E1 electric master slave. Used only for experimental purposes, this bilateral manipulator was developed in 1954. (Courtesy of Argonne National Laboratory.)

built the Handyman electrohydraulic manipulator incorporating force feedback, articulated fingers, and an exoskeletal control harness. This equipment was built for the joint AEC–USAF Aircraft Nuclear Propulsion Program (ref. 10).

—*1958.* William E. Bradley, Steven Moulton, and associates at Philco Corporation developed a head-mounted miniature TV set that enabled an operator to project himself visually into the operating space.

—*1961.* The first manipulator was fitted to a manned deep-sea submersible when a General Mills Model 150 manipulator was installed on the *Trieste* (ref. 11).

—*1963.* The U. S. Navy began deep-submergence projects, including the development of underwater manipulators.

—*1963.* R. A. Morrison and associates at Space-General Corporation constructed a lunar walking vehicle (fig. 7). This

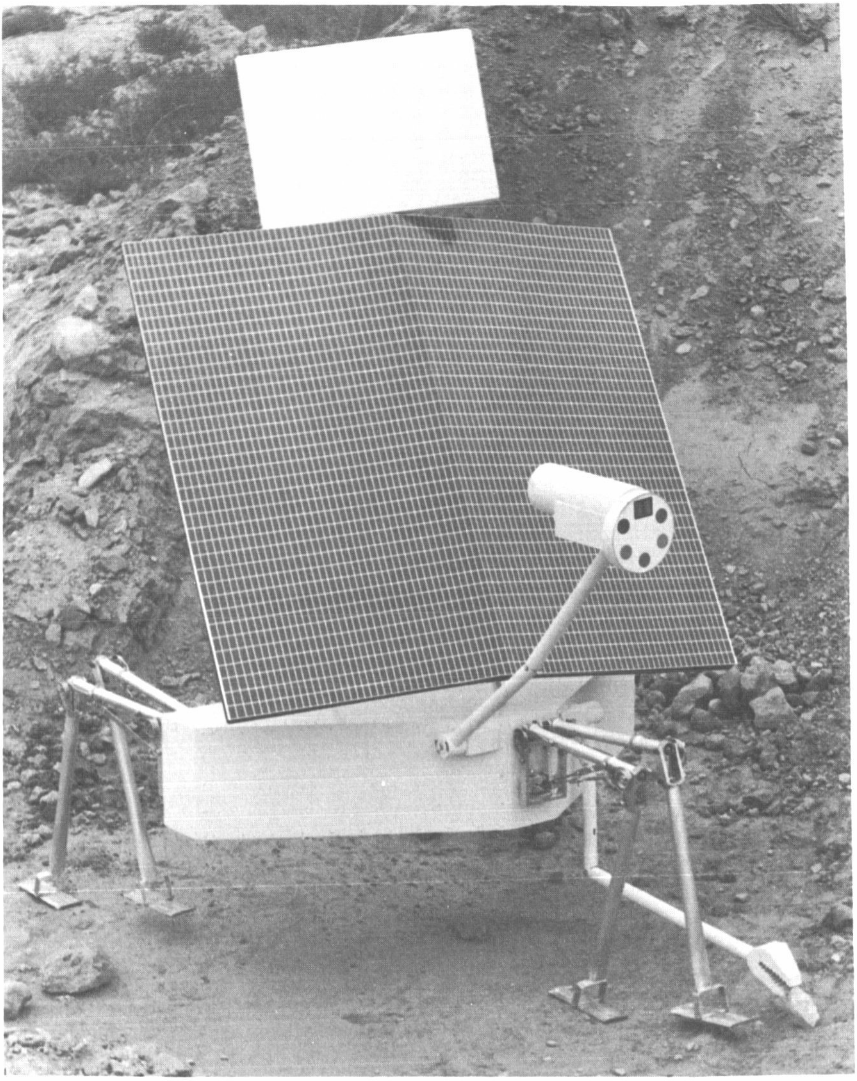

FIGURE 7.—A working model of a lunar walking machine. This six-footed walker can negotiate terrain impossible with ordinary wheeled vehicles. A solar-cell panel is mounted on top for power; and a claw-like sample collector is shown below. The walking motions are preprogrammed. (Courtesy of Space-General Corp.)

machine was later converted into a "walking wheelchair" for handicapped children (see chapter 2).

—*1964.* Neil J. Mizen and coworkers at Cornell Aeronautical Laboratory reported on the construction of a "wearable,

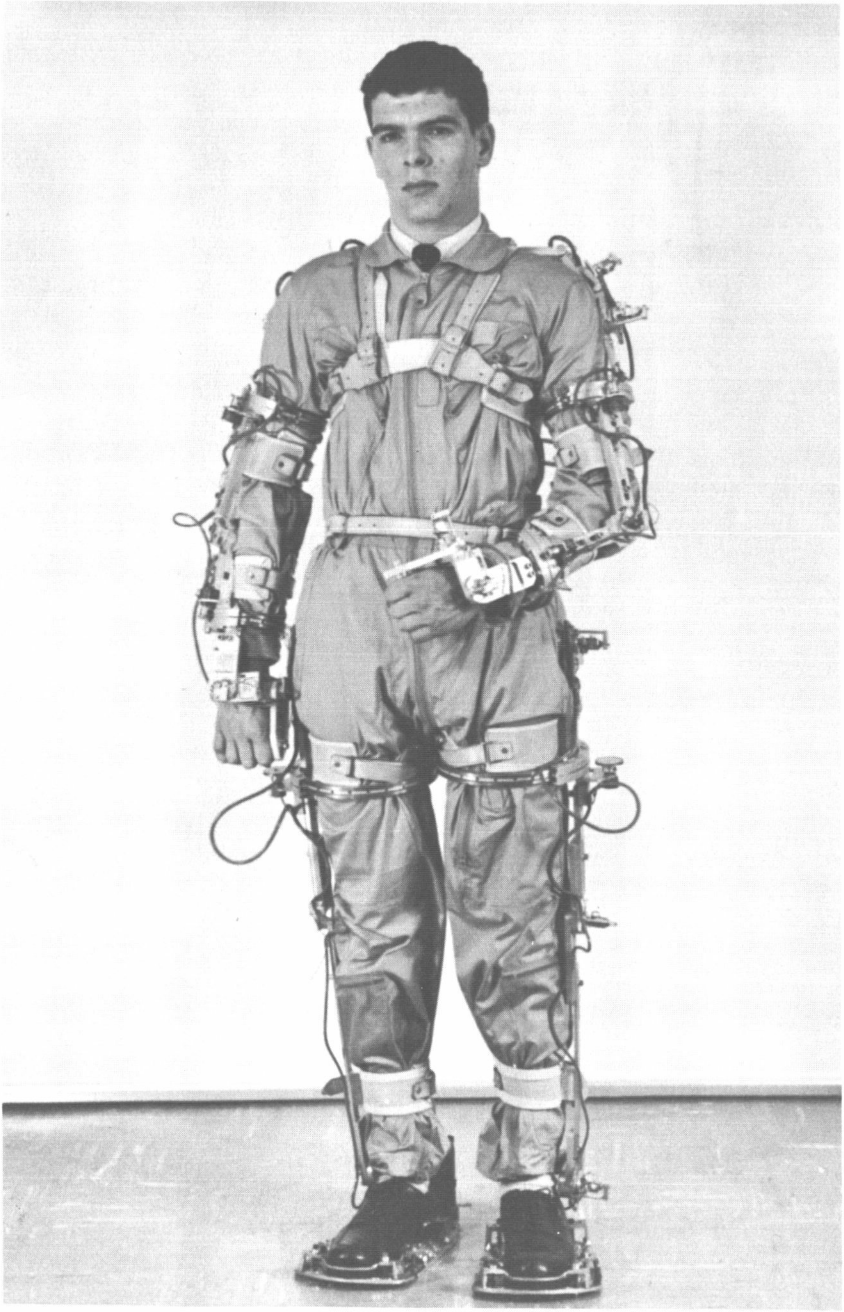

FIGURE 8.—An unpowered exoskeleton built by Cornell Aeronautical Laboratory under Department of Defense contracts. Actuators are not simulated. The exoskeleton would be a "man amplifier." (Courtesy of Cornell Aeronautical Laboratory.)

full-scale, exoskeletal structure." The Cornell exoskeleton was not powered (fig. 8) (ref. 12).

—*1965*. Ray Goertz and his associates at ANL combined the ANL Model E4 electrical master-slave manipulator with a head-controlled TV camera and receiver (ref. 4).

—*1966*. ANL combined the Model E3 electric master-slave with the Mark TV2, head-controlled TV, which added translational motion to the viewing system.

—*1966*. Case Institute of Technology, working under a NASA grant, demonstrated a computer-controlled manipulator that can perform preprogrammed subroutines specified by the operator.

This chronology gives little hint of the imminent and intimate man-machine partnership that many believe essential to the large-scale exploitation of space and the oceans. Many of the most important developments listed were made under the aegis of the Atomic Energy Commission. Further developments are likely from many sources.

CHAPTER 2

Teleoperator Applications

Since 1948, some 3,000 manipulator arms have been built in the United States. More than 80 percent were shipped to atomic energy installations where visitors can see them lined up in precision formation like well-disciplined metallic soldiers (fig. 9). These long banks of master-slaves are only the advance guard of an army of man-machine systems now being assembled to serve man in a variety of ways.

Some applications of teleoperators, such as the lifting and manipulation of a two-ton crate, or the tactile inspection of a long, narrow, serpentine passage, result from the human body's limited strength, fixed size, and restricted articulation. Most teleoperators, however, are applied in so-called "hostile" environments from which man is excluded by high temperatures, nuclear radiation, or the crushing pressures of sea water. Asbestos suits, diving gear, and space suits let man temporarily enter these dangerous realms, but his stay is usually brief and expensive.

Economy often determines the choice between man and teleoperator. It is likely to be cheaper, for example, to send a diver down to make pipe connections in shallow off-shore oil fields than to develop a teleoperator to do it. Below 100 fathoms, however, divers are encumbered by heavy suits and cannot stay down long. Deep diving is so costly that teleoperators may dominate the deep oil fields far out on the continental shelves.

The bulk of today's operational teleoperators are those unilateral and master-slave manipulators installed in hot cells to handle radioactive materials. General purpose manipulators are used because they are cheaper than a multitude of special purpose machines. Manipulators enable personnel and facilities to operate more efficiently without waiting for radioactive materials to decay to levels at which they can be handled by men directly. Ray Goertz, who pioneered the development of the master-slave manipulator at Argonne National Laboratory, estimates that the introduction of the master-slave is saving the nuclear industry well over 15 million dollars per year in operating costs and roughly 15 million dollars additional per year on special equip-

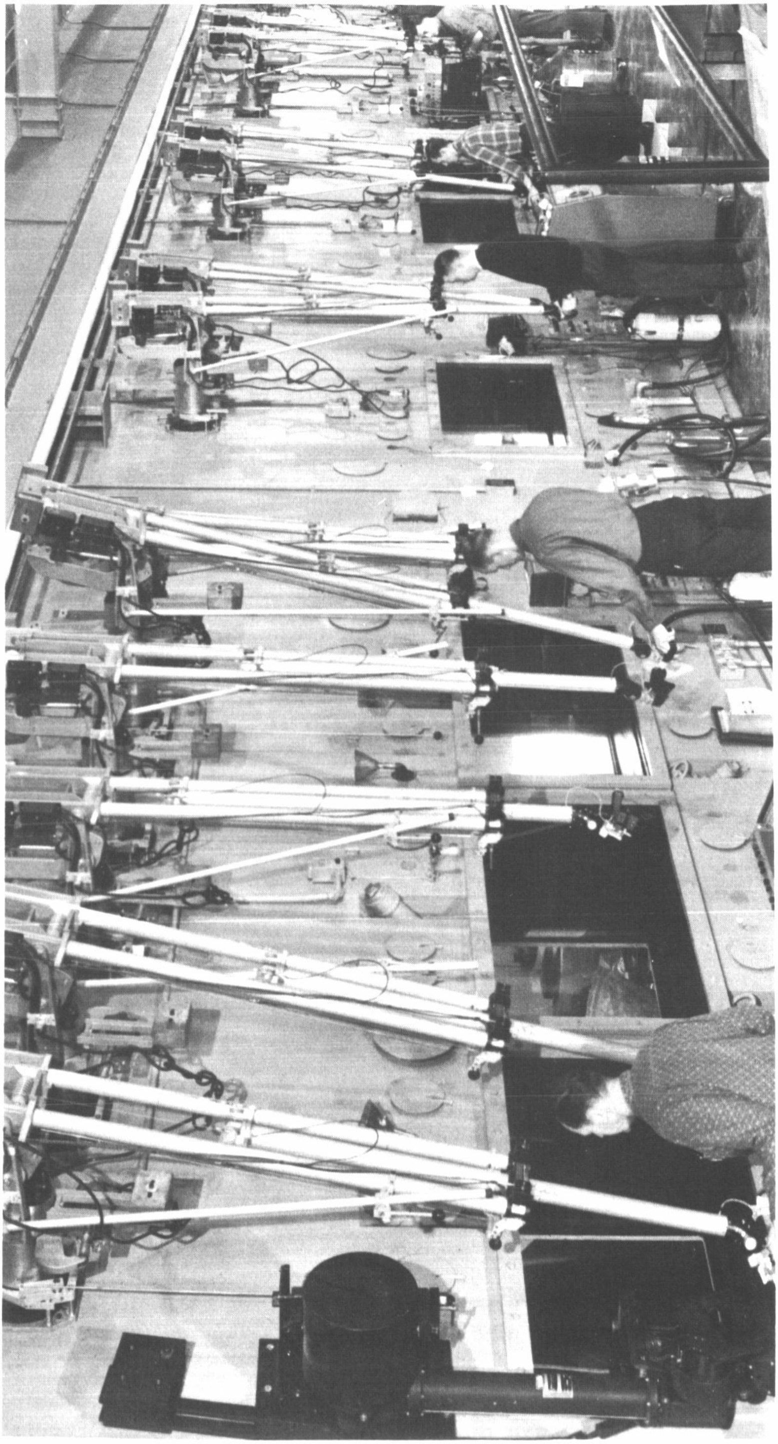

FIGURE 9.—Typical bank of mechanical master-slaves at AEC's CANEL facility, at Middletown, Conn. (Courtesy of Pratt & Whitney Aircraft.)

ment and facility costs. Teleoperators will probably succeed wherever they can muster similar, convincing economic arguments.

In summary, three considerations help determine when a teleoperator will augment man:

1. Man's absolute physical limitations in matters of strength, size, and bodily construction,
2. Human welfare and safety, and
3. Dollars-and-cents considerations.

WHAT MAKES AN ENVIRONMENT HOSTILE?

In South America, some Indians live nearly naked in the frigid winters of Tierra del Fuego; others live high on the rarefied peaks of the Andes, aided by abnormally large lung capacities. Despite man's astonishing ability to adapt to the Earth's varied climes, he often covets air conditioners or furnaces. When he enters environments more hostile than those found on the earth, he attempts to encapsulate and carry a comfortable environment along with him. The harsher the environment that a "canned man" invades, the more expensive and inconvenient the can.

One way to show how teleoperators can aid man is to list "hostile" forces and factors that man cannot handle conveniently alone. Table 1 does this and, at the same time, suggests rather intimate man-machine symbiosis. Quite obviously, this man-machine intimacy derives not only from the strength and hardiness of teleoperators, but also from their hopefully superior senses, reaction times, and abilities to handle (with the aid of computers) complex tasks. Teleoperators amplify and extend the normal man and enhance the capabilities of the physically handicapped.

Although designed to replace men in hazardous environments, teleoperators often are far from invulnerable themselves. For example: teleoperators, if they are to emulate man, must have articulated limbs and the joints must be kept free from seawater-borne silt if they are used on submersibles; in hot cells they must be lubricated with grease that does not degrade under the influence of nuclear radiation. If a teleoperator is to operate in a high temperature, the electronics subsystems in particular must be cooled to preclude degradation. Teleoperators in areas of radioactive dust or dangerous biological agents must not permit these contaminants to leak through the barrier separating man from the hazardous environment. These are only a few of the design

TABLE 1.—*Environmental Properties Affecting Teleoperator Selection.*

"Hostile" environmental properties*	Typical environments	Current solutions
High temperature	Metal-treating plants, fires	Heat shields, asbestos suits, gloves
Low temperature	Outer space, arctic regions	Space suits, insulated clothing
High pressure	Undersea	Armored diving suits and bells, teleoperators
Low pressure	Outer space, vacuum chambers	Space suits, teleoperators
Toxic atmosphere	Mining, warfare, many industrial processes	Suits and masks
Nuclear radiation	Hot cells, nuclear accidents, radiotherapy, space	Portable shields, teleoperators
Acoustic	Airfields, launch pads, rockets	Ear covers, absorbers
Hight acceleration, jostling	Aircraft, rockets, spacecraft landings	Special suits and harnesses
Zero gravity	Spacecraft	Artificial gravity
Sickening or disorienting motion	Spacecraft and other types of transportation	Drugs, stabilizers
Projectiles	Space (meteoroids), mining, blasting	Armor, shields
Biological	Warfare, laboratories	Biological barriers, quarantine, immunization, masks, gloves
High forces, heavy weights	Everywhere	Special-purpose machines (tools) teleoperators, prostheses
Complexity (too many objects, tasks, targets)	Can occur anywhere	Computer help. More than one operator
Endurance (one of the oldest reasons for introducing machines)	Can occur anywhere	Various special machines (but not teleoperators which always have man in the loop), shifts of men

TABLE 1.—*Environmental Properties Affecting Teleoperator Selection.*—Concluded

"Hostile" environmental properties*	Typical environments	Current solutions
Speed of targets	Can occur anywhere	Computer help, various special machines
Precision movement	Electronics construction, biochemical industry, surgery	Micromanipulators
Small and/or serpentine task apertures	Can occur anywhere	Various special machines, and tools, teleoperators
Entertainment	TV, stage, fairs, parades	Puppets, Disney creations
Sensory blackout (loss of visual, acoustic, and/or tactile contact)	Undersea, space, polar regions	TV, microphones, sonars, tactile probes—all are teleoperator subsystems

* Several of these properties may be present simultaneously in a hostile environment.

constraints dictated by the application. A hostile environment is also hostile to machines, but less so.

Table 2 summarizes present and proposed applications of teleoperators to various industries.

AEROSPACE APPLICATIONS

Astronauts and special purpose remote-control machines perform today's manipulative tasks in outer space. An astronaut is vulnerable, expensive, and non-expendable. Special-purpose machines, such as the Surveyor "hand" shown in fig. 10, are useful but neither dexterous nor versatile.* Dexterous, rugged, general

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*There are no well-defined "thresholds" of dexterity or versatility that separate teleoperators from tools.

TABLE 2.—*Summary of Teleoperator Applications.*

Industry	Present and/or proposed application
Aerospace	Rarely used in aircraft at present. Occasionally used in vacuum chambers and in handling propellants and explosives. Proposed for spacecraft assembly and maintenance and for exploration of Moon and planets. Man amplifiers proposed for high-g operation and cumbersome space suits. The Surveyor "hand" was a crude teleoperator (fig. 10).
Undersea	Manipulators are installed on nearly all new research and rescue submersibles. Also used for weapons recovery, ship salvage, and rescue. Used to limited extent in off-shore oil field operations and the repair and maintenance of undersea laboratories and military devices.
Nuclear	Used in hot-cell operations with radiochemicals, fuel fabrication and reprocessing, inspection of radioactive equipment, and production of radioisotopes. Used in emergency situations for inspection, rescue, cleanup, and decontamination. Used for inspection and disassembly of nuclear reactors.
Terrestrial transportation and material handling	Walking machines under development for off-road military transportation. Man amplifiers being designed to augment lifting and carrying capabilities of individual soldiers. Suggested for minefield clearing, lumber industry, warehousing, etc.
Medical	Prosthetic and orthotic devices used for many years. Walking wheelchairs and man-amplifiers proposed for handicapped. Teleoperators suggested for remote surgery and microsurgery.
Chemical and biological	Limited use in handling toxic materials, propellants, and explosives. Proposed for handling dangerous biological agents in the laboratory.
Metal processing, handling, and fabrication	Long used in forging plants and for handling large, hot metal pieces.
Electronics	Proposed for super-clean rooms and operations in toxic atmospheres.
Construction and mining	Proposed for explosive environments.
Public services	Proposed for fire-fighting and for rescue and cleanup in hazardous environments, such as gasoline, chlorine, and radioisotope spills.

TABLE 2.—*Summary of Teleoperator Applications.*—Concluded

Industry	Present and/or proposed application
Entertainment	Long used where the human operator wishes to remain concealed as in puppet shows, mechanical men, and animated creatures in à la Disney.

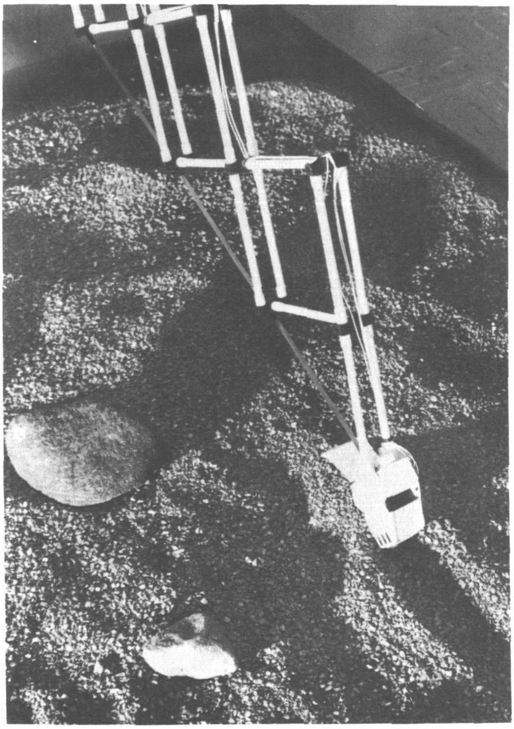

FIGURE 10.—The claw and "arm" mechanisms of the Surveyor-III Surface Sampler. On the Moon, this remotely controlled machine dug trenches.

purpose teleoperators can be further developed to aid or replace men and special purpose machines (fig. 11). Limited communication bandwidth has slowed the introduction of teleoperators but the situation is improving. William E. Bradley has suggested some intriguing advantages and disadvantages of teleoperators beyond those already suggested; viz.: hardiness, endurance, relative invulnerability, etc. (ref. 13).

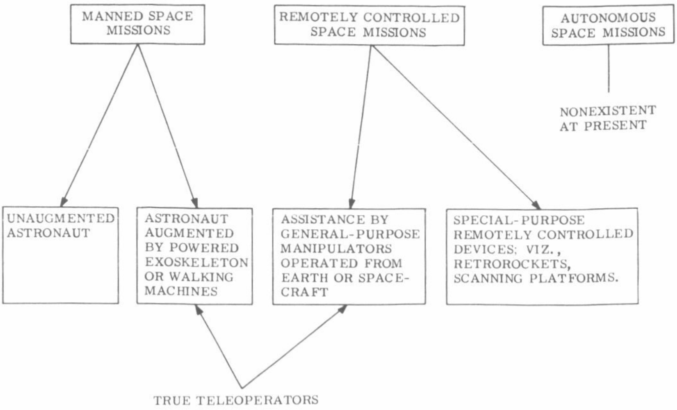

FIGURE 11.—Space missions may depend upon direct control by astronauts, upon remote control from Earth, upon autonomous (adaptive) controls, or upon some combination of these possibilities.

—A teleoperator has total recall because it is possible to record back on Earth all the machine does and sees.

—The visual scenes transmitted by the teleoperator can be easily retransmitted over worldwide television, giving viewers the sense of being direct participants in extraterrestrial feats.

—A true automaton with self-adaptive capabilities does not require the interplanetary communication capacity of the teleoperator, but the teleoperator with man in the loop should be more versatile and self-maintaining.

—At lunar and planetary distances, teleoperators suffer time-delay problems such that the Earth-based operator cannot see the results of his actions for several seconds or even minutes. This factor may severely limit the employment of teleoperators on distant missions.

Testing, Simulation and Sterilization

Radars and other avionic gear must be tested in chambers that simulate high altitudes or space conditions. Repressurization of a big chamber just to flick a console switch is obviously inefficient. A simple manipulator piercing the side of such a chamber may solve the problem. Typical of this application is the AMF Mini-Manip installed at the Norden Division of United Aircraft Corporation in Norwalk, Conn. (fig. 12). The impetus for using a teleoperator here is purely economic; chamber time and engineer's time are too expensive to waste in avoidable chamber repressurizations.

Manipulators may also find application in *very large* environmental test chambers in which full-scale manned space vehicles are tested. In 1963, the General Electric Company completed a study for the Air Force's Arnold Engineering Development Center at Tullahoma, Tenn. (ref. 14). In the large chamber studied (220 feet in diameter) manipulators were proposed for such routine tasks as the placement and adjustment of radiation sources and simple "switch-throwing" operations like those described for the Norden chamber. The manipulator would thus relieve astronauts of tasks unrelated to the vehicle tests. A more dramatic task proposed for manipulators was the rescue of astronauts should serious injuries or life-support equipment failure occur. The GE study suggested use of both long, boom-mounted manipulators and small vehicles with manipulators, similar to those built for large hot cells. Rapid chamber repressurization was not considered an acceptable solution to the rescue problem in this study.

Several persons have suggested building teleoperators in man-

FIGURE 12.—AMF Mini-Manip installed in the humidity test chamber at the Norden Division of United Aircraft Corp., in Norwalk, Conn. The manipulator hand is shown adjusting the setting on a piece of radar equipment. (Courtesy of Norden Division, United Aircraft Corp.)

like form to replace aircraft and spacecraft test pilots. A teleoperator could manipulate the vehicle's controls without risking human life but the concept is practicable *only* when the equipment being tested will eventually have a human operator at the controls; otherwise ordinary remote control could be used.

An airplane out of control may produce such violent accelerations (jostling and high-g forces) that its pilot is incapable of moving the controls or even operating an ejection mechanism (ref. 15). A powered, partial exoskeleton can come to his rescue by allowing him to move an arm voluntarily to the ejection control switch. General Electric has suggested use of a servo restraint harness system to help a pilot operate aircraft controls under high-g conditions.

Humans have dexterous hands but these same hands carry micro-organisms and various kinds of "dirt" that can and do contaminate spacecraft parts during construction. Even a carefully masked and clothed human may carry some aura of microbes and "dirt." Here lies one of the major problems in the aerospace and many other industries: clean assembly (ref. 16). Why not master-slave use manipulators for parts assembly? This is the radioactive hot-cell problem in reverse: i.e., keeping contamination out instead of in. This is still virgin territory for teleoperators.

Satellite and Deep-Space Operations

The spectrum of tasks proposed for teleoperators in orbit and deep space is so broad that a list is in order to provide perspective.

—Satellite inspection to identify status, malfunctions, or fix its purpose and country of origin.

—Satellite capture and de-spin.

—Satellite maintenance and repair, particularly space vehicles incorporating nuclear power plants or propulsion systems.

—Satellite turn-off, supposing its "killer timer" has malfunctioned.

—Attachment of deorbiting rockets.

—Satellite destruction or disarming of military satellites.

—Satellite assembly and test. The erection of large space antenna arrays has been suggested as a promising application for teleoperators (ref. 13).

—Removal and/or replacement of experiments and samples (such as coupons to measure micrometeoroid damage).

—Satellite experiment modification, rearrangement, or adjustment; viz., changing filters and photographic plates in an orbiting telescope.
—Aiding spacecraft docking.
—Propellant and cargo transfer, particularly if the cargo is hazardous.
—Astronaut rescue, which might involve satellite de-spin, forcible entry, and transfer of a man to a rescue vehicle.
—Exoskeletons to improve an astronaut's mobility and dexterity.

Many of the above needs might arise during the same mission. Since it would be inefficient to build a different machine for each task, one of the selling points of space teleoperators is their versatility and generality. As a consequence, most studies of teleoperators for space and deep-sea work have focused on general purpose vehicles bristling with manipulator arms. Space vehicles carrying teleoperators bear such fanciful names and acronyms as Remora, Humpty Dumpty, Man Friday, and MEMU. The reader may consult the Glossary for guidance.

A major NASA study effort was completed in 1966 when Ling-Temco-Vought (LTV) and Argonne National Laboratory (ANL) investigated a Maneuvering Work Platform (MWP) and a "Space Taxi" with attached manipulators for Marshall Space Flight Center (ref. 17). This was a study of the utility of a manned maneuvering space capsule on such potential missions as the Manned Orbiting Laboratory (MOL), the Apollo Applications Program (AAP), the Manned Orbiting Research Laboratory (MORL), and the Orbiting Launch Facility (OLF). Later chapters will cover the MWP and Space Taxi concepts in more detail.

Many orbital teleoperator concepts look like extra-terrestrial bugs. Generally, man is enclosed in a spherical or cylindrical capsule under shirtsleeve conditions. He controls special arms that grasp the target and firmly anchor the space capsule to it. Other controls move the working arms outside the capsule. Because space is precious on spacecraft (and on small submersibles), the master side of space manipulators is usually miniaturized. Figure 13 shows one conceptual design for an orbital capsule (refs. 18 and 19).

Planetary Operations

Exploration of the Moon and other planets thus far has fallen to unmanned, special-purpose remote-control machines such as Rangers, Mariners, and Surveyors. Remote control on such space

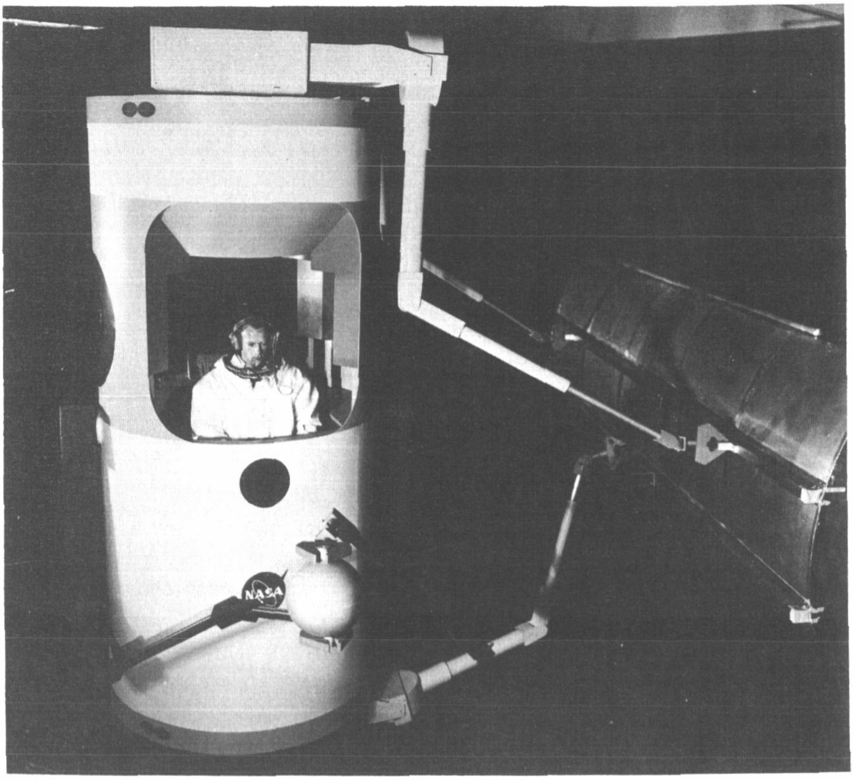

FIGURE 13.—Mockup of the Space Taxi designed by Ling-Temco-Vought and ANL for NASA's Marshall Space Flight Center for orbital repair and maintenance work. A complete Space Taxi would have three docking arms, and two "working" arms.

vehicles is confined to switch throwing and the initiation of programmed sequences; viz., Mariner's planetary-scan platform. With teleoperator arms and hands, an Earth-bound operator could direct manipulations impossible with special-purpose remote-control systems. With teleoperators on a large, unmanned, planetary lander one might:

—Vary, adjust, and modify experiment layouts,
—Maintain and repair equipment, and
—Collect and handle samples with great flexibility.

NASA's Automated Biological Laboratory (ABL), for example, might benefit from Earth-controlled manipulators. The ABL would then be analogous to the undersea Benthic Laboratory conceived by Scripps Oceanographic Laboratory and discussed later in this chapter.

Two major disadvantages of employing teleoperators to study the Moon and planets are (1) the time-delay factor, and (2) the very wide bandwidths needed to handle television and control signals for a many-jointed teleoperator. The precise point at which teleoperators may become cheaper and more effective than limited purpose, remote-control exploratory machines like the Surveyors is not known.

UNDERSEA APPLICATIONS

Almost all of the ocean floor is at least two miles deep. Even on the shallow continental shelves, divers rarely work below 100 fathoms. The military threat of hostile vehicles and installations makes it imperative that we know how to work under water. Substantial petroleum reserves under the deeper portions of the continental shelves have given commercial impetus to undersea technology. Undersea manipulators have already recovered debris from the sunken *Thresher* and an errant H-bomb, though with great difficulty in each instance.

Although many operational problems of inner and outer space are similar (viz., the necessity of firmly anchoring the teleoperator vehicle to the target), the environments have radically different effects on teleoperator design. The undersea teleoperator is surrounded by a good heat sink, but one that is extremely corrosive and laden with silt and biological agents. The tremendous pressures at great depths preclude the common mechanical master-slave linkages between the control and actuator spaces. The sensor problem is also different. Instead of the bright sunlight of orbital space, there may be such darkness that an operator cannot see a manipulator hand which is only a few feet in front of his viewport.

Both in outer space and under the sea men may have to identify, build, maintain, repair, recover, or destroy some object. These activities require cleaning, bolting, cutting, welding, replacing parts, etc.—just the things men's hands do to terrestrial, dry-land equipment. In the oceans the missions may be for (1) scientific research, (2) commercial operations, or (3) military operations.

Undersea Scientific Research

The small, manipulator-equipped submersible is common to all three mission classes. In early bathysphere descents, scientists were passive observers. Even the simplest manipulators widen

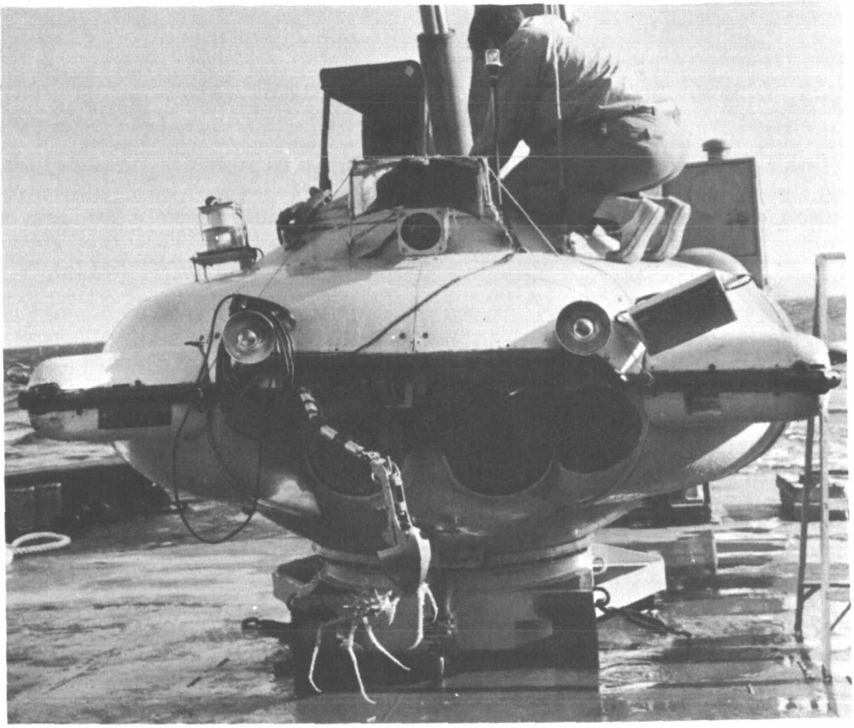

FIGURE 14.—The hydraulically actuated manipulator (called a "clamshell grab") on the Diving Saucer SP-300 holding a spider crab. (Courtesy of Westinghouse Electric Corp.)

research horizons considerably, as fig. 14 demonstrates with Cousteau's Diving Saucer and its manipulator-captured nimble prize. A more advanced submersible concept is the North American Aviation, Inc., *Beaver* in fig. 15. Manipulator-equipped submersibles include the *DOWB, Alvin II, AUTEC I, Trieste II, Deepstar,* and *Aluminaut* (ref. 20). These are general purpose utility craft capable of manipulating objects outside of the protective hull sheltering the human operator(s). (See Glossary for more information on submersibles.)

Selective sampling is much more effective than hit-or-miss dredging from surface ships. Submarine geology will profit immensely as manipulators bring back rocks, nodules, and deepsea ooze samples. Shells, plants, and the more sluggish forms of marine life are targets, too. Manipulators can also set up, maintain, and repair such undersea scientific equipment as gravimeters, current meters, seismometers, corers, and penetrometers. For archeologists, submersibles such as *Asherah,* fitted with teleoperators, can retrieve artifacts and help with underwater excavations.

Victor C. Anderson, of Scripps Institution of Oceanography (University of California), has described the Marine Physical Laboratory's Benthic Laboratory: an unmanned, self-repairing, self-maintaining, ocean-floor capsule fitted with manipulators (ref. 21). The Benthic Laboratory is built according to a modular philosophy that enables the manipulator located inside to replace electronics components and modify experimental setups (fig. 16). The "autonomous" nature of the Benthic Laboratory has much in common with self-contained hot cells that operate sealed up for years. Such a capability is ideal for *in situ* scientific experiments both on the ocean floor and on distant planets. One of the first uses of the Benthic Laboratory will be to support a "sensor

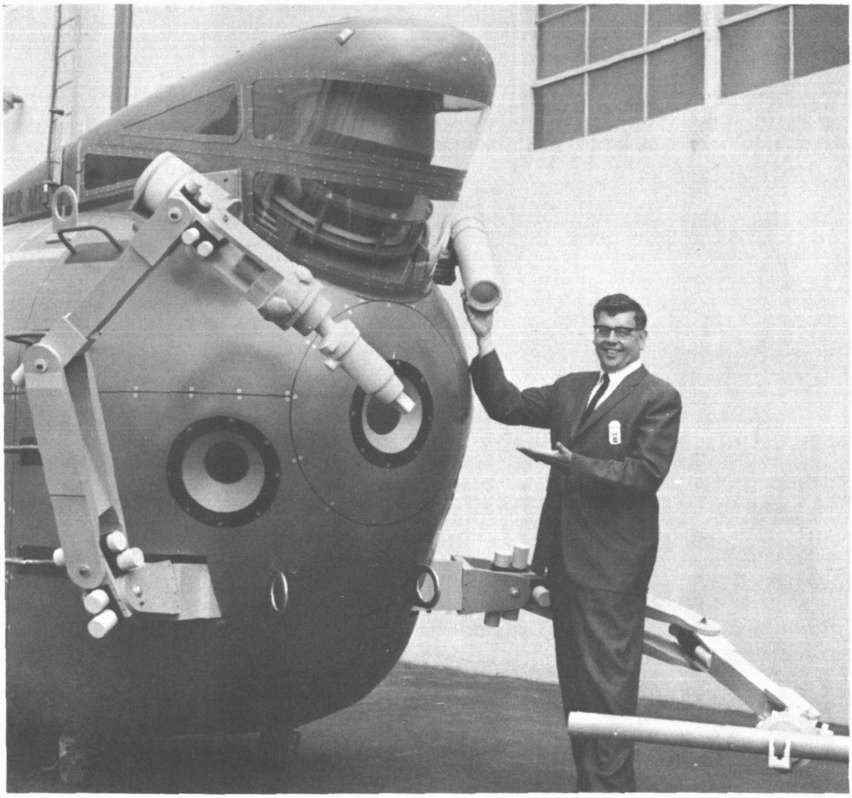

FIGURE 15.—A mockup of the *Beaver* submersible, showing two manipulator arms. (Courtesy of Ocean Systems Operation, North American Aviation Inc.)

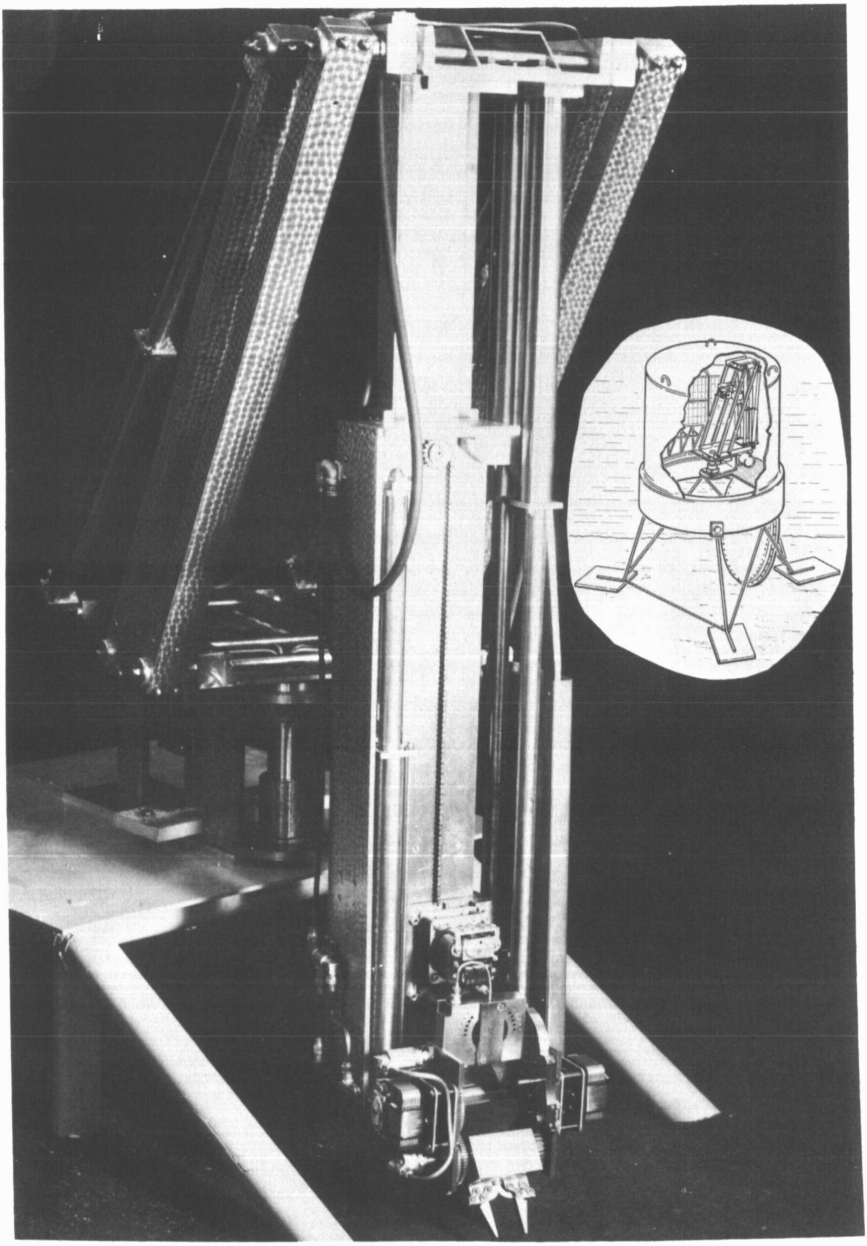

FIGURE 16.—In the Benthic Lab concept: an internally mounted manipulator can modify experimental setups and carry out maintenance and repair operations. (Courtesy of V. C. Anderson, Scripps Institution of Oceanography.)

field" of current meters on the floor of Scripps Canyon off California.

Another teleoperator concept is the bottom crawler equipped with manipulators, lights, and television. Except for the trailing power and control cable, the Scripps remote-controlled, underwater manipulator (RUM) vehicle (fig. 17) might be considered the "wet" analog of NASA's lunar and planet crawlers. The missions of RUM-type vehicles would be similar to those of the small submersibles. The sea bottom, however, is treacherous territory, and "hovering" submersibles have proven to be more versatile and mobile.

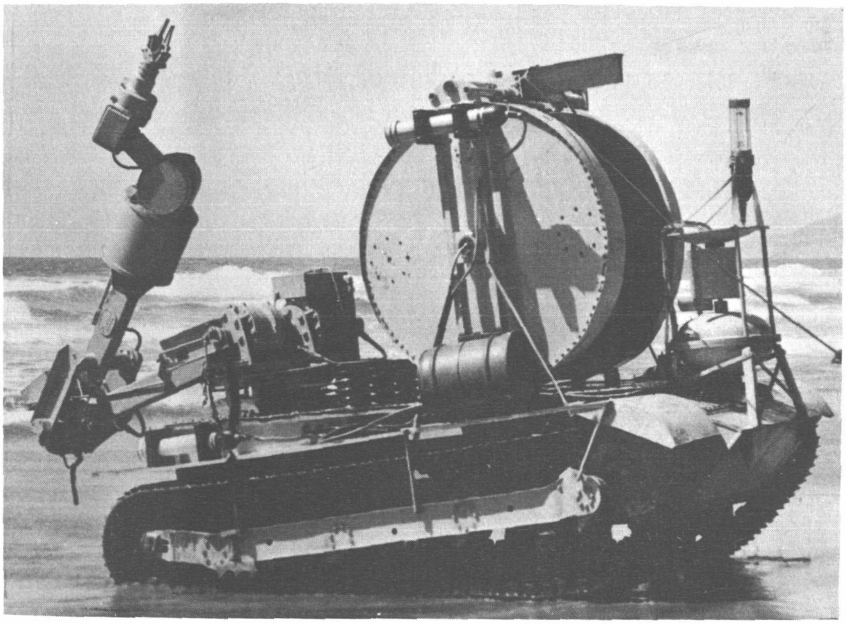

FIGURE 17.—RUM (Remote-Controlled Underwater Manipulator), a cable-controlled, tracked vehicle equipped with a General Mills Model–500, electric unilateral manipulator mounted on a hydraulically driven boom. (Courtesy of V. C. Anderson, Scripps Institution of Oceanography.)

Walking machines are of questionable merit on the sea floor because of the precarious footing. A powered exoskeleton, however, might materially aid a heavily armored diver by permitting him to work longer and carry out tasks requiring more than human strength.

Commercial Underwater Operations

In 1966 more than 1800 offshore oil wells were operating from surface platforms in an average depth of 200 feet of water. Divers currently perform the many underwater tasks necessary to bring an offshore well into production. Drilling operations, however, are moving out into water so deep that divers can work in it neither effectively nor for long periods. With few exceptions, the manipulator-equipped small submersible is the instrument attractive to the interested oil companies. The same submersibles built for underwater research may help bring in petroleum from the continental shelves.

Task surveys show a wide range of jobs for teleoperators:

—Surveying and selecting drill sites,
—Preparing the drill sites,
—Observing and assisting during drill string landing,

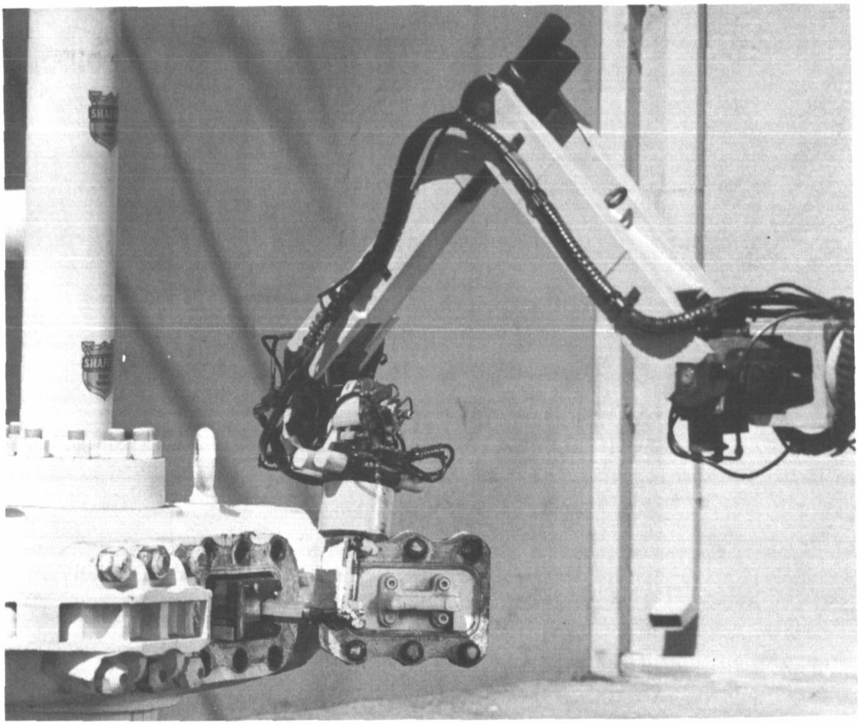

FIGURE 18.—Simulation showing a hydraulic unilateral manipulator replacing a blowout-preventer ram used in offshore oil-well work. (Courtesy of Ocean Systems Operation, North American Aviation, Inc.)

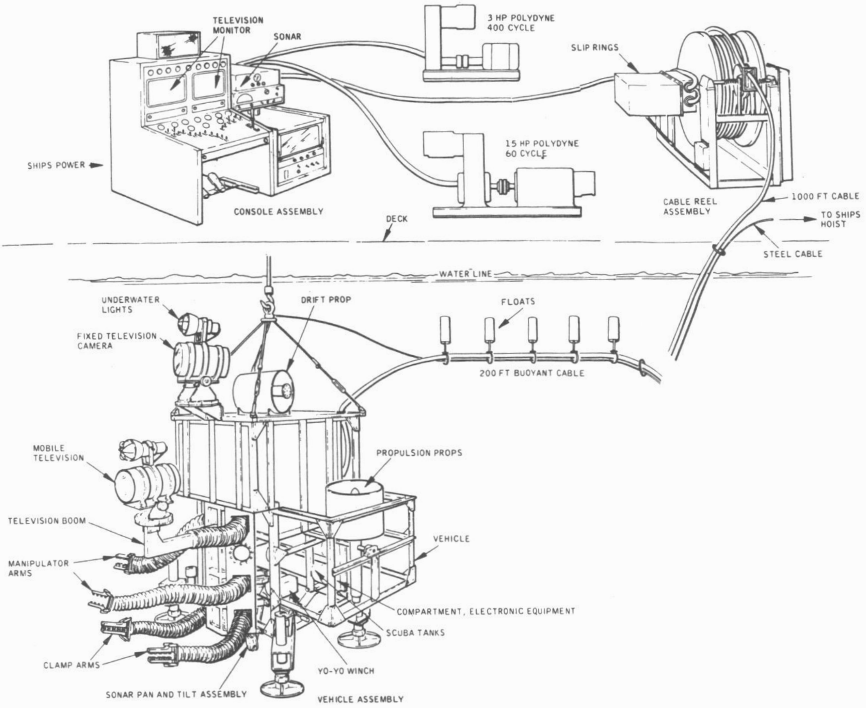

FIGURE 19.—Schematic showing UNUMO underwater teleoperator built for oilfield work by Hughes Aircraft. (Courtesy of Hughes Aircraft Co.)

—Replacing of blowout-preventer rams (fig. 18),
—Making "completions"; i.e., pipe connections,
—Replacing and patching pipe sections,
—Recovering objects dropped from drill platforms,
—Removing marine growth, and
—Routing and installing pipelines.

Hughes Aircraft Company built the UNUMO and a MOBOT for trials in offshore oil fields* (ref. 20) before the advent of the small submersible. The UNUMO was a ship-suspended teleoperator carrying lights, attachment arms, manipulators, television camera, and a propulsion system (fig. 19). Its mobility and versatility were limited, however, and it was never put into operational use. Hughes also built a version of the MOBOT for the Shell Oil Company for undersea trials, but it has not had widespread use.

An intriguing commercial application of teleoperators is in

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*See the Glossary for acronym definitions.

salvage work—or even treasure hunting. Hunley and Houck report that the submersible *Recoverer I* has been employed in raising a 165-foot sunken fishing vessel off Cape Lookout, North Carolina (ref. 20). Some representative manipulator tasks were clearing away debris and rigging, attachment of flotation containers, slinging cables, closing valves, and placing explosive charges for cutting away standing rigging.

A much-advertised commercial aspect of deep-sea exploration has been mining of the manganese nodules that pave many sections of the ocean floors. Picking up these nodules one by one with manipulators would not be economical, but teleoperators could certainly be employed in surveying and sampling nodule fields for eventual mining.

In all commercial applications, the indifference of teleoperators to time, fatigue, and the hostile properties of the deep-sea environment is of fundamental economic importance. Keeping ships at sea and divers on the bottom are costly operations. The advantages of around-the-clock teleoperators are obvious.

Military Underwater Operations

Small unmanned, sea-floor stations perform the same functions as navigation and reconnaissance satellites. Like their space cousins, they must be installed, maintained, and repaired, and such tasks may warrant further development of teleoperators.

The *Thresher* catastrophe in 1963 and the H-bomb recovery off Spain in 1966 reinforced the status of teleoperators in undersea military activities. The H-bomb was recovered by a teleoperator called CURV (Cable-controlled Underwater Research Vehicle), which the U. S. Naval Ordnance Test Station had previously employed for operations such as torpedo recovery (ref. 22). CURV is equipped with high resolution sonar, television camera, three screws for propulsion, and a rather crude claw for grasping objects (fig. 20).

The *Thresher* incident spawned a series of small submersibles, similar to those employed in scientific and commercial activities, but for personnel rescue. The first submersible in this series to be built was the *DSRV–1* (Deep Sea Rescue Vehicle) and Lockheed Missiles & Space Company was the prime contractor. The *DSRV–1* is a small, nuclear-powered submarine, transportable in a C–141 and piggyback on a submarine. Manipulator hands will clear away debris, cut cables, and help the *DSRV–1* mate ("dock" in space lingo) with a stricken submarine and begin rescue.

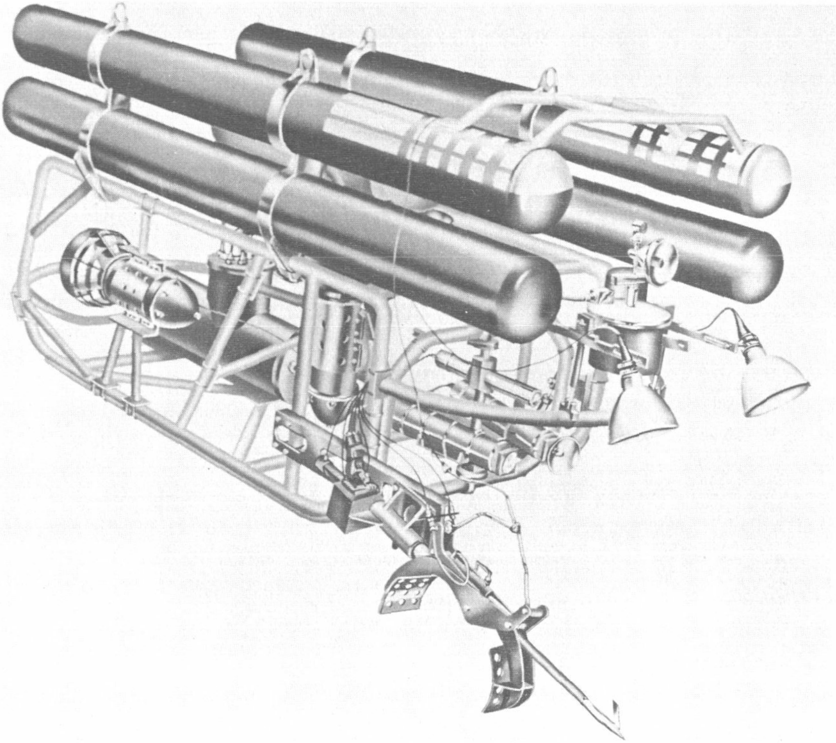

FIGURE 20.—CURV (Cable-Controlled Underwater Research Vehicle) was designed for torpedo recovery. It retrieved the H-bomb lost off Spain in 1966. (Courtesy of Naval Ordnance Test Station, Pasadena.)

NUCLEAR INDUSTRY APPLICATIONS

The plutonium production plants of the Manhattan Project produced the first large quantities of radioisotopes during the early 1940's. The glove boxes previously employed in handling toxic materials proved completely inadequate in the highly radioactive "cells" at Hanford, Oak Ridge, Los Alamos, and other AEC installations. Long tongs alleviated the problem somewhat, particularly those with ball joints that could work through hot-cell walls, and crane operators became very adept at "manipulating" hot cargo with hooks and special attachments. Nevertheless, more dexterity was desperately needed in radiochemistry and nuclear fuel operations, and the nuclear industry is now the largest user of teleoperators.

During the nuclear weapons program, chemists faced the job of untangling hundreds of radioactive fission products found in spent nuclear fuel. They also had to develop chemical processes for extracting the plutonium from irradiated uranium fuel slugs. Once the plutonium was recovered, ways had to be found to dispose of liquid wastes—some so radioactive that they boiled spontaneously. After weapons tests, radioactive fallout had to be monitored and analyzed. The upshot of these requirements was that chemical and physical manipulations with hot materials ran the full spectrum of tasks found in conventional chemical laboratories: i.e., pouring, stirring, powdering of samples, loading furnaces, titrating, collecting evolved gases, and similar deft handling jobs. To carry out such operations through several feet of concrete and lead, chemists have learned to work with master-slave manipulators.

Hot laboratories offer so many examples of teleoperator applications that it is impractical to list them all. The bank of manipulators in fig. 9 is typical of the hundreds of hot laboratories around the world. Many glove boxes and specialized remote-control devices are still used, too. Remotized saws, drills, balances, and grinders carry out much of the repetitive work, while the manipulators are reserved for nonroutine operations, such as setting up a lathe and handling samples.

Fuel Fabrication and Reprocessing

As nuclear power has become a big business, fuel fabrication and reprocessing have moved out of the laboratory onto the production line. The more automated the production line, the less need there is for general purpose manipulators. Nevertheless, automated equipment must be maintained and repaired; if the production or reprocessing line is very hot, manipulators will be installed for these functions. There is also a small but significant residue of tasks that cannot be automated, such as the retrieval of errant fuel pellets. Just as the most highly automated factory still employs human workers, nuclear fuel production plants will always have manipulators.

The fabrication of fuel elements from fresh uranium rarely requires more than glove-box operation because radiation levels are low. Today most reactor fuel is made without manipulators. However, as "recycle" fuel (i.e., "unburnt" uranium and plutonium from reprocessed "spent" fuel elements) enters fuel fabrication plants, glove boxes must give way to hot cells. Plutonium-240 and other radioactive constituents make recycle fuel impossible to handle safely with glove boxes.

Such fuel-handling problems plagued the designers of the EBR–II (Experimental Breeder Reactor) Fuel Cycle Facility at the

AEC's National Reactor Testing Station in Idaho (ref. 23). Hot spent fuel pins from the EBR–II had to be processed and the extracted, still-fissionable fuel refabricated into new fuel elements for reinsertion in the reactor. The circular production line is illustrated in fig. 21. Long fuel assemblies pulled from the reactor enter at the left and move counterclockwise around the circle. The external metal tube is first stripped, then the enclosed fuel pins are melted and refined. After the unfissioned fuel is extracted by wet chemistry, it is fabricated into new pins. With manipulators helping at each step along the way, new fuel enters the reactor at the completion of the circle.

The EBR–II Fuel Cycle Facility was originally designed to be more highly automated than practical considerations finally permitted. For example, the fuel-pin dimensions could not be controlled with sufficient accuracy to be acceptable to all automated fuel-handling equipment on the line. In anticipation of such problems, master-slaves and specially designed, radiation-resistant unilateral manipulators had been installed and they were able to

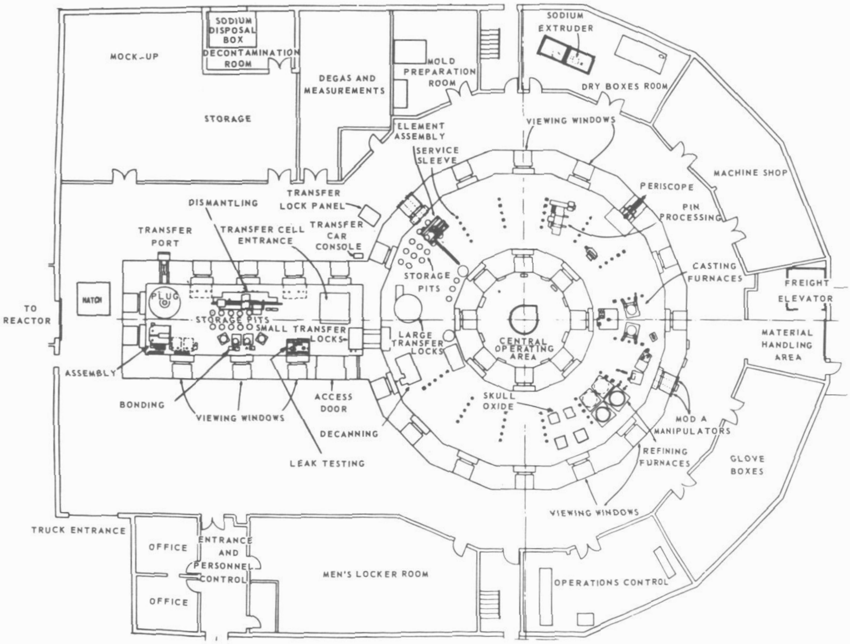

FIGURE 21.—Plan view of the EBR–II Fuel Processing Facility. Assisted by manipulator pairs at most windows (only one pair shown), fuel moves counterclockwise and back into the reactor (ref. 23).

take over when automatic equipment faltered. In terms of the original design, the manipulators were partly redundant as far as fuel handling was concerned. Redundancy turned out to be good design practice, for the EBR Fuel Cycle Facility has operated successfully and continuously for more than three years without human entry.

Nuclear fuel fabrication and reprocessing generally require high-load-capacity manipulators with large working volumes. Electric unilateral manipulators are used in preference to master-slaves in most applications of this type.

Handling Power Plants

Some of the largest teleoperators have been built for disassembling reactors destined for nuclear rockets and aircraft. During the development of these high-temperature engines, reactors are tested in a remote site and then carried to large hot cells (fig. 22), where they are stripped down piece by piece, fuel element by fuel element, to determine what transpired during the tests. Even after extensive cooling periods, these reactors are still radioactively hot and can be dissected only by long-reach, heavy-duty manipulators. In the nuclear rocket program, 14,000-pound, hot NERVA reactors are taken from the test stands to the E–MAD building (Engine Maintenance, Assembly, and Disassembly), in Nevada, where "rectilinear" manipulators in the Wall Mounted Handling Subsystem (WMHS) systematically disassemble them (ref. 24). Some representative tasks are:

—Removing propellant lines, transducers, test wiring, etc.,
—Removing pressure-vessel bolts,
—Unclamping control-rod actuators,
—Unclamping and removing thrust structures,
—Removing bolts from turbopump flange and removing turbopump,
—And so on, until the fuel elements can be removed for detailed examination.

Engine-handling philosophy in the nuclear rocket program evolved directly from the Aircraft Nuclear Propulsion (ANP) Program, which also was concerned with large, hot engines (ref. 25). In addition, the disassembly tasks closely resemble those in the AEC's SNAP (Systems for Nuclear Auxiliary Power) reactor program. The major difference is size—a SNAP reactor has the dimensions of a waste basket rather than an automobile (ref. 26).

In the acre-sized hot cells or "bays" used for aerospace reactor

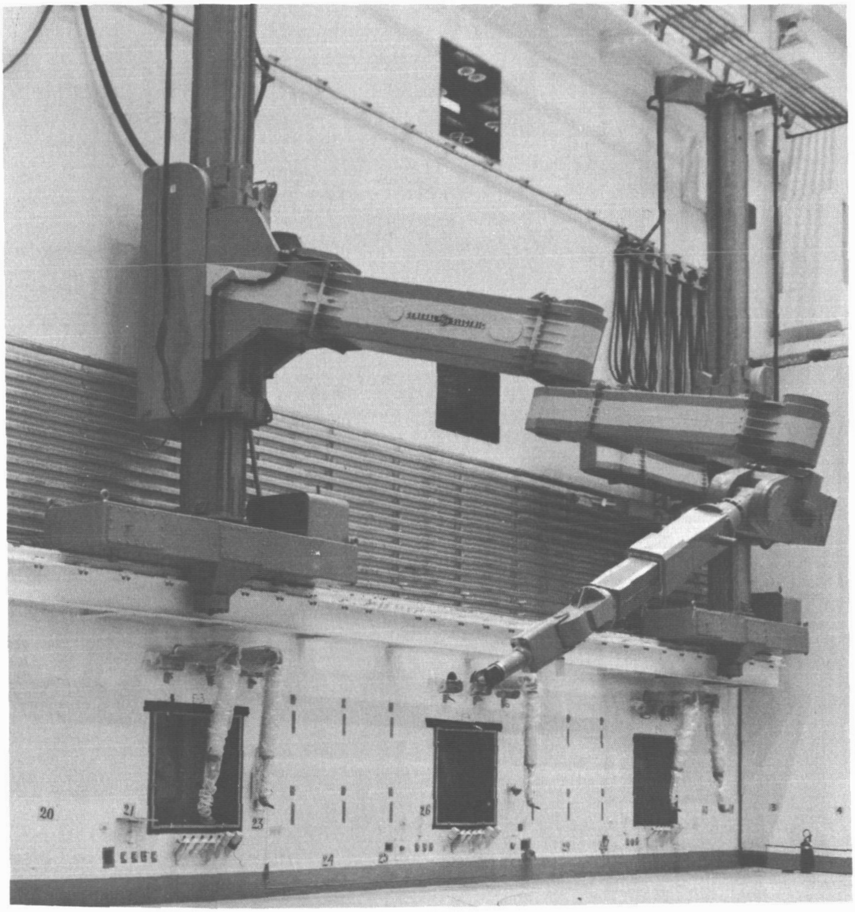

FIGURE 22.—The GE electric unilateral manipulator booms comprising the Wall-Mounted Handling System (WMHS) in the E-MAD building at the National Rocket Development Station (NRDS) in Nevada. This photograph was taken inside the E-MAD main bay. PaR electric unilateral arms are installed on the ends of the booms.

programs, small mobile manipulators can do many odd jobs, such as retrieving dropped parts unreachable by the main manipulators. Although the operating volumes of the large manipulators intentionally overlap, there is always the possibility that one will break down leaving parts of the hot cell inaccessible for a period. Mobile manipulators then come into action. Because of their usefulness, most large nuclear installations have one or more mobile manipulators (ref. 27). The PaR–1 vehicle (fig. 23) built by Programmed and Remote Systems Corp. is typical.

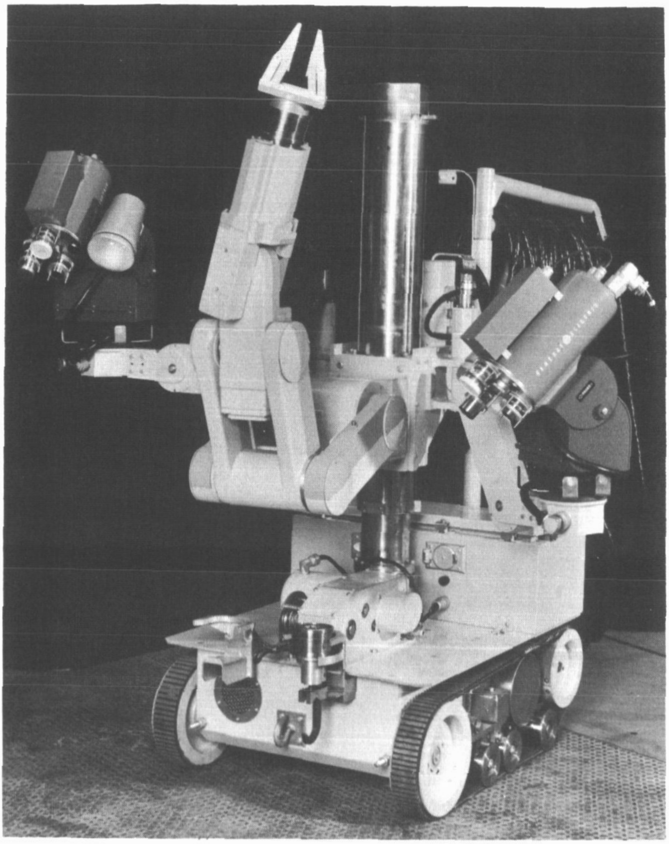

FIGURE 23.—The PaR–1 mobile manipulator. The vehicle is powered and controlled by cable. The manipulator arm and the two TV cameras are mounted on articulated booms. Height of the central support tube is 68 inches. (Courtesy of Programmed and Remote Systems Corp.)

Between flights, a nuclear aircraft engine*—unapproachable because of induced radioactivity—would have to be serviced like other aircraft engines. A special vehicle, the Beetle, fig. 24, was developed during the ANP program for this purpose. Protected within a shielded cab, the operator could approach the engine and make limited repairs and adjustments. Because of its mobility and general purpose manipulator, the Beetle could also have been employed in crashes and other emergency operations.

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*Although considerable development work was directed toward the construction of a nuclear aircraft engine (ANP Program), no operational engines were built.

FIGURE 24.—The Beetle, a manipulator-equipped nuclear emergency vehicle. (AEC photograph.)

Nuclear Emergencies

Teleoperators are valuable in emergencies because they are mobile, versatile, dexterous, and relatively immune to environmental forces fatal to man. The same qualities that make them useful in rescue and salvage operations in space and under the sea carry over to the nuclear industry.

In a nuclear emergency, a teleoperator could enter the hostile environment, ensure that no further nuclear excursions could occur, measure radiation levels, reconnoiter the area, clean away debris (often with cable cutters, torches, etc.), and retrieve personnel (refs. 28 and 29). Time is critical in a nuclear accident because radiation levels may kill survivors before a facility has been brought under control by shutting off electricity and fluids, and fighting fires.*

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*One school of thought contends that personnel rescue must be consummated so rapidly that there would be little time to bring up teleoperator support. In this view, humans must enter the accident area and rapidly retrieve the survivors.

Since nuclear incidents are rare, cleanup may also entail finding out exactly what went wrong. Debris must be recovered and much of it taken to hot cells for careful inspection. Finally, the facility must be decontaminated, a procedure involving sweeping, vacuuming, and washing with special chemicals. Time, of course, permits radioactive cooling, and removal of hot fuel and irradiated components further reduces radiation levels around the site of an accident.

Although a wide range of mobile manipulator systems exists (ref. 27), none has been developed especially to deal with a major accident. Small mobile units like the PaR–1 can be helpful, but they are not designed for rapid entry via stairs, narrow passageways, and debris-cluttered floors. In a sense, using them is like using an ordinary automobile instead of a fire truck for fighting fires. As commercial nuclear power plants proliferate, specialized rescue vehicles—comparable in purpose to the Navy's *DSRV–1*—may be constructed.

So far, very few nuclear emergencies have occurred and development reactors have been intentionally located far from cities. In the now-cancelled ANP program, though, the AEC and Air Force pondered the possibility that a plane with hot engines might come down in a populated area, and three vehicles with rather strange names were built: the Bat, the Masher, and the MRMU (Mobile Remote Manipulating Unit). The Bat and Masher had no manipulators. The Bat was a shielded vehicle intended primarily for tractor operations, while the Masher boasted a crane. MRMU was a radio-controlled vehicle carrying two manipulator arms built by the Air Force Weapons Laboratory specifically for nuclear recovery operations. These vehicles are rarely used now.

The Alternating Gradient Synchrotron (AGS), at Brookhaven National Laboratory, on Long Island, has enough beam power to induce dangerous levels of radioactivity in the accelerator tunnel. Radiation levels occasionally exceed 100 roentgens per hour, precluding direct handling of the equipment. New accelerators now on the drawing boards will induce even higher radiation levels. Although most induced radioactivity decays rapidly with time, the time of a huge accelerator like the AGS is so expensive that downtime must be minimized. Consequently, Brookhaven has conceived of a master-slave manipulator that can quickly enter accelerator areas to repair and replace components or modify experiments. A servo system for this manipulator has already been developed (ref. 30). Because many accelerator parts are fragile, Brookhaven adopted the force-reflecting servo manipulator scheme pioneered at Argonne National Laboratory.

Some radiation-processing facilities also are expensive to operate. Although food, wood, plastics, and other materials usually go through irradiating zones on conveyor belts or automatic transport equipment, a need may arise for maintenance, repair, and modification of a production line without shutting down the source of radiation (reactor or radioisotope source). Teleoperators may turn out to be economically desirable in such facilities.

TERRESTRIAL TRANSPORTATION

Once a vehicle leaves the smooth, hard, expensively prepared roadbeds that criss cross well-developed countries, wheels may become a liability, and legs may serve us better again.

Most walking machines built to date have been for development and demonstration purposes, although R. A. Liston reports that some crude draglines have been constructed employing walking machines (ref. 31). There is also a rather slow and ponderous walking machine in a German mine. These primitive machines, however, have been preprogrammed and therefore are not true teleoperators.

General Electric Company has carried out considerable study and development work on multilegged vehicles. Originally termed CAM's (Cybernetic Anthropomorphic Machines) or "pedipulators," such machines may replace men and animals on warfronts where roads (especially unbombed and unmined ones) are rarities. Walking machines also might be advantageous in swamp and polar exploration.

Are there also other ways in which teleoperators can aid soldiers? The so-called "man amplifier,"* an exoskeletal machine, can conceivably transform an ordinary soldier into a "super-soldier." A controllable, powered framework surrounding a soldier might amplify his strength and, at the same time, carry a protective shell. In effect, the soldier might become a walking tank, carrying a variety of heavy armament and still possessing much of the versatility and mobility of an individual. Cornell Aeronautical Laboratory, which pioneered exoskeletal work for the Navy, calls this the "servo soldier" concept. The exoskeleton can be magnified into an armored biped controlled by a man inside wearing a harness that communicates his arm and leg motions to the teleoperator. When man does not "wear" the machine,

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*The term "man amplifier" was coined by Cornell Aeronautical Laboratory. A similar word, "maximan" has been coined by E. G. Johnsen to describe the teleoperator augmentation of man.

the machine is no longer a true exoskeleton, but rather a man-controlled walking machine and also a true teleoperator.

Exoskeleton work continues under the joint Army-Navy Project MAIS (Mechanical Aids for the Individual Soldier). One specific concept is "Hardiman," an exoskeleton enabling a man to lift up 1,500 pounds six feet in five or six seconds. Such a feat should even impress the Martians who invaded the Earth in walking machines in H. G. Wells' "War of the Worlds."

ARTIFICIAL LIMBS

A good artificial limb is dexterous, general purpose and operated by a man, and these are the key ingredients of this book's definition of a teleoperator.

A *prosthetic device* attempts to duplicate the functions of some missing part of the body. The tasks of a prosthesis are thus often those of a human hand, an arm, or a leg.

An *orthotic device* helps some weakened or atrophied part of the body to gain strength and dexterity. It does not replace a limb; a good example would be a powered exoskeletal brace to strengthen and steady a weakened arm. Training and exercising various parts of the body also are important applications of teleoperators. Medical engineering and teleoperator engineering overlap here.

Where engineering disciplines meet, intellectual cross fertilization often occurs. Medical engineering, for example, has developed ingenious joints, clever linkages, and sophisticated mechanical hands that grip harder when objects tend to slip. Aerospace engineering can provide better power sources, servomechanisms, and extensive knowledge of feedback control. Just where a more general and intimate confrontation will lead no one knows.

Teleoperators divorced from the body save for controls and sensors can also help people whose strength, freedom of motion, and dexterity are somehow limited. Feeding machines can be built wherein a specialized mechanical hand manipulates table utensils under direct control of the person being fed. Teleoperators could turn book pages, play cards, write, tune TV sets, and give the bedridden greater independence.

Wheelchairs are common external mechanical aids and are classifiable as teleoperators if they have some dexterity that can be controlled by the occupant. The walking "wheelchair" built by Space-General Corp. (fig. 25) was derived directly from Space-General's work on lunar walking machines. A walking wheelchair has the advantages of good maneuverability and the capability of

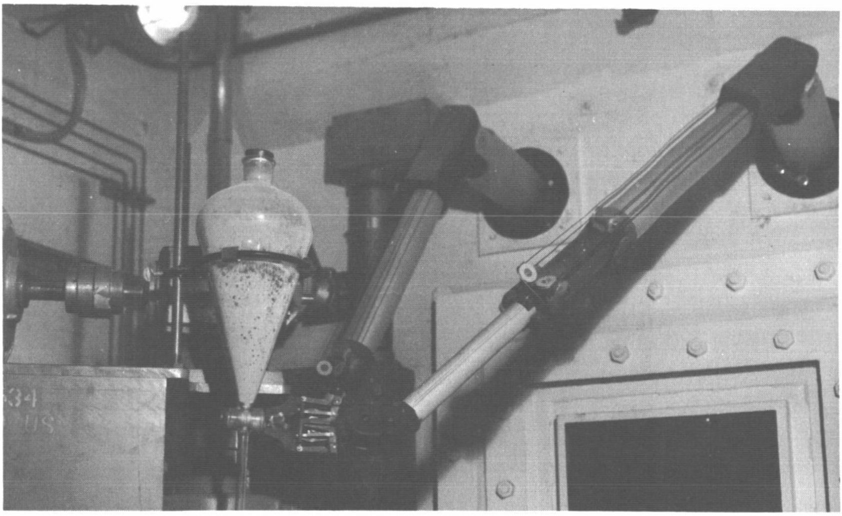

FIGURE 25.—The walking "wheelchair" evolved from Space-General's work on lunar walking machines (fig. 7). The prototype shown here was built for the Child Amputee Prosthetics Project of the University of California at Los Angeles. It can maneuver in sand, mud, and rocky soil, as well as climb over small obstacles. Steerable, leg action is preprogrammed. (Courtesy of Space-General Corp.)

traversing rough terrain and climbing low steps and curbs. "Leg" motion, however, is preprogrammed, and the walking wheelchair is not quite a teleoperator.

Teleoperators may eventually come to the surgeon's aid. At least three applications are now envisioned as teleoperators become more sophisticated:

- —Superclean surgery. Already operations have been performed with the patient completely enveloped by a sterile barrier of thin plastic. The plastic is so thin that the surgeon can work through it in glove-box fashion. Teleoperators of high dexterity and with considerably better touch feedback than now available could make truly aseptic surgery possible.
- —If clean surgery is feasible via a teleoperator, it is conceivable that a surgeon can operate from almost any distance. This idea is not an unreasonable extrapolation of electrical master-slave manipulators with force reflection.
- —Microsurgery is another target for teleoperators. Electrical

circuits and mechanical devices can steady and scale down a surgeon's motions to any desired degree. Hand tremors can be damped out. With image magnifiers and intensifiers, work of great precision can be carried out in a way not too different from methods of connecting microelectronics circuits.

A more controversial application of teleoperators in medicine would be their use in the manipulation of the limbs and heads of brain-damaged children in a technique called "cross patterning." Experiments at The Institutes for the Achievement of Human Potential, in Philadelphia, have shown some improvement in the capabilities of such children through lengthy therapy of this type. Possibly teleoperators can supplant some of the lay therapists now employed; however, present thinking tends toward preprogrammed, computer-controlled machines rather than teleoperators.

One certain byproduct of the development of teleoperators and man-machine systems is a better understanding of the human body and its many subtleties. For example, the study of electromyography* for teleoperator control will undoubtedly lead to greater insight into the body's own control mechanisms.

INDUSTRIAL APPLICATIONS

Accidental detonations sometimes occur when the constituents of explosives and rocket propellants are mixed, particularly during the development of new and unpredictable compounds. For many years technicians handled these powerful chemicals behind barricades with crude tongs and specialized mechanical devices (ref. 32). As in nuclear work, the dexterity of these simple devices left something to be desired. Today, dozens of mechanical master-slave and unilateral manipulators, identical to those employed in hot cells, manipulate and blend hazardous chemicals.

An excellent example of the utility of manipulators in the explosives industry can be seen in figs. 26 and 27, which show explosives handling stations at du Pont's Eastern Laboratory. The shambles shown in fig. 27 resulted when one pound of explosives detonated in a beaker held by a manipulator hand. The operator located behind the barricade felt nothing, because the shock was absorbed by the teleoperator linkage. Edwards Air Force Base uses a similar manipulator set up for mixing rocket propellants (fig. 28).

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*Electromyography is the study and utilization of the electrical potentials generated by muscle activity.

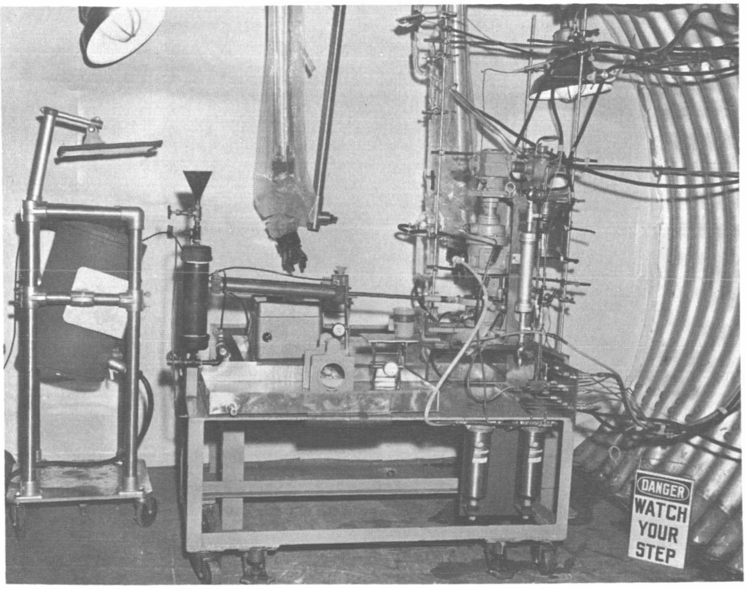

FIGURE 26.—A laboratory bench and manipulator used in developing high explosives. (Courtesy of Dupont Explosives Dept., Gibbstown, N.J.)

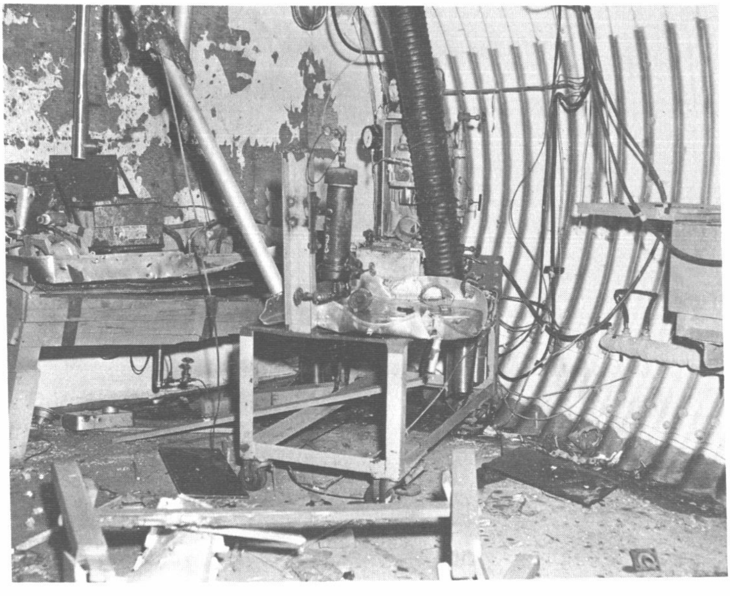

FIGURE 27.—A laboratory setup similar to fig. 26 after one pound of explosive in a beaker exploded while it was being held in the manipulator hand. The operator did not even feel the shock. (Courtesy of Dupont Explosives Dept., Gibbstown, N.J.)

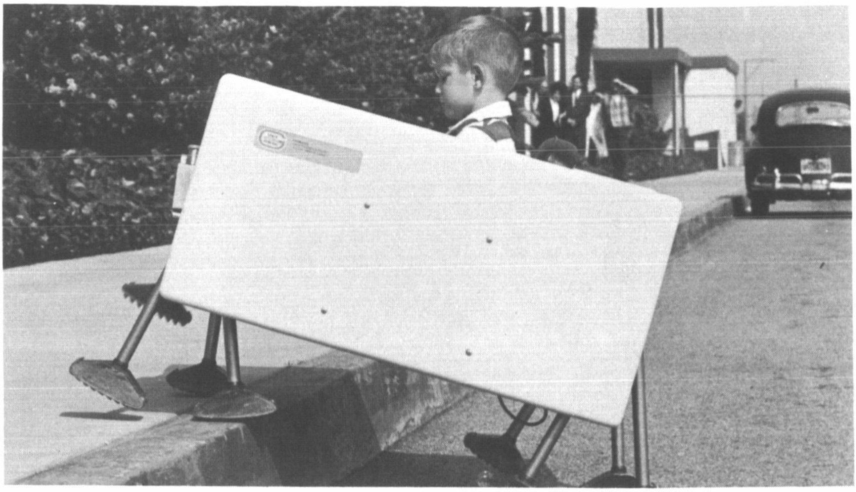

FIGURE 28.—A pair of manipulator arms employed in propellant development at Edwards Air Force Base, Calif. (Courtesy of Edwards Air Force Base.)

Many chemicals are toxic or irritating when handled. These, too, could be handled by manipulators.

Normally, a glove box is adequate protection for biologists, although the least pin prick in the glove can be fatal in some work. In 1960, the Army's Biological Warfare Laboratories, Fort Detrick, Md., evaluated master-slaves and other remote-control devices to prevent personnel infection from biological agents and laboratory animals (ref. 33). The Army ultimately concluded that more careful control of conventional techniques would be adequate. Nevertheless, the report remains an important part of the telemechanism literature because it is full of special and ingenious designs of teleoperator hands for handling animals, syringes, and other biological apparatus. Under severe circumstances, such as the environment following a biological attack, teleoperators might prove invaluable in decontamination and cleanup.

Metal-Industry Potentialities

Teleoperators usually appear wherever the environment endangers man or the objects to be manipulated are too large or heavy for him. In forging operations, metal ingots are so hot that men cannot work close to them, and, even if they could, ingots are too heavy to handle manually. The obvious solution is a heavy-duty manipulator that can pick up a hot ingot, carry it to the forge, and manipulate it as desired (ref. 34). Some forging manipulators are permanent fixtures, but others are mobile. Capacities range as high as ten tons. Forging manipulators have little dexterity and are special purpose machines; therefore, it is stretching a point to call them teleoperators.

Another application where high temperatures favor teleoperators is the maintenance of high-temperature furnaces. Here, heat-resistant teleoperators could enter the furnaces long before men could, inspect the interior, and make repairs where necessary. Furnace downtime would be minimized.

High-vacuum production processes might benefit if man's dexterity could be transferred through vacuum chamber walls. High-vacuum welding and high-vacuum metal production both require deft operations that man could do with the help of teleoperators. Downtime for maintenance and repair could be reduced. There is a close economic parallel between this application and the use of manipulators in high-altitude test chambers in the aerospace industry.

It is intriguing to apply the teleoperator concept to fabrication and maintenance problems in industry. A highly flexible arm can explore, and manipulate in spaces so tortuous and confined that human arms are completely barred. Aircraft welding, the cleaning of pipes and retorts, and searching for broken bits in drill holes are but a few possibilities.

The Electronics Industry

In the old days, a radio amateur could build a passable rig in his basement—even in poor light and next to the coal bin. Now rows of women in dust-free garments assemble electronic parts under microscopes in clean rooms. Cleanliness and miniaturization beckon teleoperators. The electronics clean room workers combat dirt and airborne contaminants because solid-state components are notoriously sensitive to impurities. Welds and solder joints, too, suffer in the presence of dirt. In fact, the lure of higher performance may eventually place most microelectronics and integrated circuit construction in a vacuum or controlled atmosphere. Micromanipulators worked by personnel outside the "superclean" room may then assemble and fabricate the desired equipment. Most of the micromanipulators employed by the electronics industry today, however, are special purpose tools with little dexterity. They operate from controls like those on lathes and other machine tools and have few of the attributes of the human hands. The large numbers of repetitive operations make tool specialization profitable here.

Construction and Mining

Steeplejacks, sand hogs, and skyscraper riveters have romantic but hazardous jobs that teleoperators could do. Men still do such work because teleoperators are expensive to develop.

Mining has become less dangerous in recent years; excavating machines have sent much of the work force back to the surface. Tunneling is still hazardous and time consuming. When explosive charges are placed, men and machines retreat before the detonation and move back in gingerly afterward. Conceivably, a heavily armored teleoperator could be constructed that would continuously place drill charges and detonate them against the working surface. It would then leave behind a path of suitably fragmented material for supporting mucking machinery to convey back to the minehead. Furthermore, there would be no need for ventilation and other provisions to support and protect fragile men.

PUBLIC SERVICE APPLICATIONS

Armored, superstrong policemen and firemen have been suggested (mostly in jest) by more than one engineer. Super-criminals may well appear first; they have on television. A fire, whether in a warehouse or forest, poses an environmental threat that a teleoperator can counter with its great resistance to heat and independence of a breathing atmosphere. No teleoperator has yet been designed for this purpose, but tasks, such as hose handling, application of chemicals, preparation of firebreaks, and so on, are easy to imagine.

Public service officials also must deal with spills and releases of toxic gases and fluids. Releases of chlorine for example, have frightened many communities. Truck and train wrecks have often spilled noxious substances in populated areas. Perhaps someday a general purpose teleoperator will be built to cope with such situations without endangering man.

In February 1966, the Chicago papers related how a lipstick-sized capsule of radioactive cobalt was accidentally dropped at the Lutheran General Hospital. The technicians loading the source into its container fled and received only a small radiation dose. To retrieve the cobalt source, personnel from Argonne National Laboratory ran a PaR–1 mobile manipulator (fig. 23) into the area, picked up the source with the manipulator, and dropped it in its lead container. A teleoperator was the hero in this mishap.

Safeguards stipulated by the AEC have prevented undue exposure of the public to radiation. As we progress farther into the atomic age, however, a state or large city may find it worthwhile to add teleoperators to its line of emergency vehicles to deal with nuclear accidents.

FROM PUPPETS TO SERVANTS

Aboard the Santa Fe and Disneyland Railroad, passengers can see lifesize ostrich dinosaurs drinking from a vanishing waterhole. Other prehistoric monsters search for food and fight among themselves. The monsters are preprogrammed and controlled by Disney's Audio-Animatronics system. By removing the preprogramming limitation, some P.T. Barnum of the future can fill parades and circus rings with giants, monsters, and gladiators that duel to the death. Indeed, combat by teleoperator might become a fad like the current "crash" contests between jalopies. Instead of manipulating arms and legs by strings like the puppets of yore, electromagnetic and audio signals bring life to these machines.

What a status symbol a walking-machine golf caddy could be! To future generations no safari or mountain-climbing expedition may seem complete without teleoperators to clear the trail, carry supplies, and tote the elephant tusks back to camp.

The "Far, Far Out" category of concepts includes the Man Multiplier or "Doppelgang," in which one man controls tens or even thousands of identical machines, all making the same motions simultaneously in concert with the human operator. The reader's imagination may generate applications for this idea.

The "Miniature Man" concept is also remote, although there is no fundamental reason why teleoperators cannot be built much smaller than man as well as larger. Several imaginative scientists have toyed with the idea of building a teleoperator able in turn to build a smaller replica of itself, and so on, smaller and smaller, until the descendants reach atomic dimensions. Science fiction, yes; but all vital fields have their wild frontiers, and teleoperators are no exception.

CHAPTER 3

Subsystems and Their Integration

The arms, legs, and hands of a teleoperator inevitably attract the most attention because they are the most nearly human portions of the machine. Yet, to fulfill man's objectives in outer space, under the sea, and elsewhere, a teleoperator must be capable of propelling itself from place to place, communicating its position and operational status to man, and, most important, effectively projecting man's presence into the environment being explored. The complete teleoperator, therefore, has an array of subsystems that make it a sentient, mobile, and hopefully, profitable extension of man.

When teleoperator complexity greatly exceeds that of primitive unilateral manipulators, conceptual visualization becomes easier if the system is broken down into subsystems. Any such dissection is arbitrary, but the subsystems portrayed in fig. 29 have proven useful in teleoperator analysis and design. The ten teleoperator subsystems can be defined in terms of functions and typical hardware:

—*The actuator subsystem* carries out manipulations, walking, and other dexterous activities ordered by the human operator. The actuator subsystem is the "effector" portion of the teleoperator system. The slave arms and hands of the familiar master-slave manipulators are typical actuator subsystems.* Yet, it is too restrictive to imagine actuator subsystems as always anthropomorphic. (See table 3 for definitions.) Wrist extension, unlimited wrist rotation, and lack of elbow joints already make some master-slave manipulators nonanthropomorphic to a degree. Tomorrow may see suction grips, telescoping legs, and many-jointed arms; viz., the Serpentuator concept. Of course, teleoperator actuator subsystems may also be stronger and more precise than man's limbs and hands.

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*The motors and other devices that *create* motion are often called "actuators."

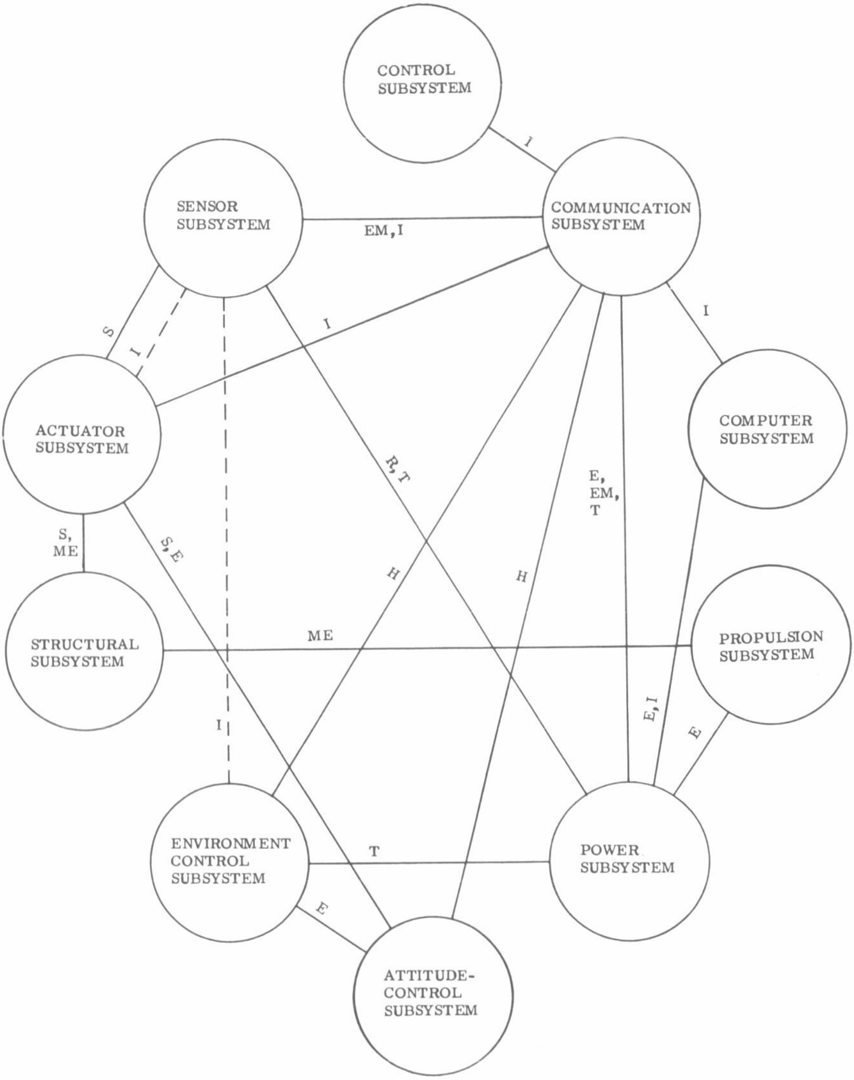

FIGURE 29.—Interface diagram for teleoperators. Some of the most important interface forces between subsystems are indicated by the following code: S = spatial, E = electrical, EM = electromagnetic, R = radiative, ME = mechanical, T = thermal, I = information. (See fig. 30 for examples.) A dotted connecting line indicates a local control loop that bypasses the control subsystem, such as a thermostat temperature control.

—*The sensor subsystem* is the sentient portion of the teleoperator. It may see, feel, hear, smell, or otherwise sense the environment, giving the operator rapport with trans-

TABLE 3.—*Definitions of Some Common Types of Teleoperators.*

Type	Definition used in this book
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 overhead 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.
Anthropomorphic teleoperator	A teleoperator with controls and an actuator subsystem resembling the human body. An exoskeleton *must* be anthropomorphic to a large extent; many manipulators possess fingers, wrists, and shoulder joints, etc. At best, this is a vague and relative term.

actions in the actuator space. More than any other subsystem, the sensor subsystem enables man to project himself across distance and through barriers into the working area. Television cameras, microphones, piezoelectric pressure pickups, infrared cells, sonars, and navigation gyros are only a few of the possibilities. Like the actuator subsystems, many sensors are nonanthropomorphic. The sensor subsystem also tells the operator the "status" of the teleoperator by relaying data on vehicle location, velocity, attitude, and the system operational mode.

—*The control subsystem,* including, of course, the human operator, analyzes the information fed back by the sensor subsystem and prepares new commands to the various subsystems. In the most obvious case, the operator sees an object and moves controls that cause a manipulator to pick it up or otherwise manipulate it. Or, a status indicator may signal that an attitude-control actuator is not functioning, causing the operator to take corrective action. The purview of the control subsystem extends far beyond the master portion of a master-slave manipulator or the switch-type controls of a unilateral manipulator. To illustrate: since a teleoperator is mobile in the generalized case, the control subsystem also receives and analyzes navigational information and dispatches appropriate commands to the propulsion and attitude-control subsystems. The control subsystem is the teleoperator's brain, decision maker, and command generator.

—*The communication subsystem* is the nervous system of the teleoperator (see fig. 29). To it and from it speed all data and commands. Hard wire, electromagnetic, sonar, and mechanical links tie all of the subsystems to the control subsystem in those cases where the operating space cannot be seen directly by the human operator. When hot-cell windows and submersible portholes permit direct visual access, the data-handling capacity of the communication subsystem is augmented by a visual channel of great bandwidth. Direct vision represents a superlative communication link.

—*The computer subsystem* aids man in controlling the teleoperator. In this function, the computer converts incoming information into displays that the operator can easily comprehend. It makes calculations and predictions to support and improve decision-making by the operator. Further, the computer may relieve the operator's burden by storing command subroutines that can handle the more perfunctory teleoperator tasks. For example, stowing the manipulator on a submersible can be carried out entirely by stored subroutines. In distant (viz., planetary) operations, where signal time delay and bandwidth are restrictive, a small computer in the actuator space can compress data for transmission back to the operator. Hopefully, this same computer can also give the teleoperator some degree of autonomy and quick reaction. (See later discussion in this chapter.)

—*The propulsion subsystem* may comprise rockets, motor-driven wheels, screws, or leg-like parts of an exoskeleton, depending upon the application.

—*The power subsystem* provides electrical, hydraulic, mechanical, and other forms of power to the various subsystems. The energy source may be man himself (as in mechanical master-slaves and some prostheses), a battery, a solar-cell bank, compressed gas, an internal combustion engine, etc.

—*The attitude-control subsystem* employs jets, propellers, electromagnets (in space), telescoping structures, docking arms, and a variety of other devices to stabilize and control the spatial orientation of the teleoperator. In some cases, the actuator subsystem itself may provide the necessary forces for attitude control. Commands for attitude control may come directly from the operator, but very often the operator will be short-circuited by local control loops, such as those used for maintaining a satellite's Earth orientation.

—*The environment-control subsystem* maintains temperatures, pressures, atmospheric composition, and other environmental parameters within specified limits. Heaters, cooling elements, and various kinds of life-support equipment are available for these functions. Like attitude control, a suitable environment is usually maintained, without conscious effort on the part of the operator, through the use of local control loops; viz., thermostat-controlled electronic compartments.

—*The structural subsystem* unites and supports other subsystems. In teleoperators, of course, the system is, as a whole, often divided physically by an environmental barrier or by great distances. In orbital and deep-sea missions, the operator commonly resides within the teleoperator vehicle, but this is certainly not a necessary arrangement.

Schematic isolation of each subsystem from the teleoperator-as-a-whole aids the engineer by setting before him limited sets of related functions. It is easier to grasp and visualize the hardware form of the communications subsystem, for example, when it lies separated from the complexities of the overall system. Balancing this advantage is the problem of glueing the separated subsystems back into a viable, unified system.

SUBSYSTEM INTERFACES

In practice, no one ever designs a subsystem without thought for the overall system and the objectives that have been assigned to the teleoperator. Design cannot proceed on the basis of admonishments alone; teleoperators are too complex for that. The so-called "systems approach" disciplines the conceptual designer and the applications engineer alike. The systems approach permits the luxury of subsystems excision without overall system degradation caused by poor interface matching when the subsystems are reassembled.

The first step in the systems approach is the definition of the system and its component subsystems—something just done for teleoperators. Next, the performance of the teleoperator must be expressed in terms of some overall figure of merit. In military systems, the over-riding figure of merit is often "cost effectiveness." For a manipulator engaged in some sort of production activity, the figure of merit might be measured in fuel elements handled per hour, or perhaps in more abstract terms as the time taken to assemble a standardized test object by a skilled operator. The speed and versatility of various manipulators can be compared on a standard basis if such a scale of value can be established. Of course, cost, maintenance requirements, and reliability are also important. The point here is that objective design of any complex system requires some definition of excellence that can be optimized by varying system parameters and, in turn, subsystem design. Needless to say, much design work, some of it excellent, proceeds with a lot less objectivity than that afforded by systems analysis.

Assuming the value of the systems approach in teleoperator design, we are immediately faced with the unsettling fact that nearly all teleoperators are applied in non-routine, non-standard operations that are not easily characterized by some single figure of merit. What is the figure of merit for a teleoperator prowling the Martian surface or a deep-sea rescue vehicle retrieving crewmen from a sunken submarine? Teleoperators are valuable because, with man in the loop, they can cope with unpredictable, unmeasurable events. The versatility that makes teleoperators valuable also makes them difficult to analyze.

If an overall figure of merit can be conceived and formulated in terms of subsystem parameters, the establishment of subsystems specifications is easy. The subsystem is designed to the range of parameters that optimizes the performance of the whole teleoperator system. Without guidance from systems analysis, engineers resort to intuition and experience. Most teleoperators move from concept to operational status via this road precisely because they are generalized machines rather than specialized systems that can be optimized to do a specific job.

Experience and intuition, if they are to guide subsystem integration, must be formulated verbally and shared among engineers. Let us take a specific example to see how this can be done. A power subsystem designer may be asked to provide a package that will yield a kilowatt of electrical power for six months and weigh less than 1,000 pounds. Environmental conditions and other parameters must also be specified if the power plant is to work properly when the subsystems are all assembled. Superimposed on these *subsystem specifications,* drawn most likely from rough feasibility studies, certain guidelines or *design philosophies* are also set down. One well-established design philosophy in manipulator design is that of *spatial correspondence*; that is, a motion in the control space should be duplicated in the actuator space. This is a design consideration that depends to a large extent upon the type of work to be done. Nevertheless, it has considerable value to a manipulator designer over and above narrow specifications such as lifting capability, reach, and so on.

System performance specifications, when interpreted as subsystem specifications and design philosophies, figure critically in reuniting subsystems into an effective whole. Still another kind of specification tells us more about the inner workings of the integrated teleoperator. This is the *interface specification.* Very succinctly, the interface specification tells the designer just what interface conditions—voltages, heat fluxes, data rates, etc.—he will have to provide if his subsystem is to mesh neatly with the nine adjacent subsystems.

Nine important interface "forces" exist in any teleoperator. The thermal interface specification allows the designer to bridge the thermal interface between, say, his power plant and the communication subsystem; it may stipulate specific temperatures and heat fluxes on the exterior of the power plant in such a way that they will not compromise the sensitive electronic gear in the communication subsystem. Examples of other interface forces are given in fig. 30.

Between the ten teleoperator subsystems are $10 \cdot 9/2 = 45$ interfaces, each bridged by a possible nine types of interface forces. Obviously, all interface forces are not important in teleoperator design. A little thought weeds out the trivialities, leaving the major interfaces portrayed in fig. 29. Of course, the importance of some of these interface bonds varies with application. To illustrate, the mechanical interface between the control and actuator subsystems is vital in mechanical master-slave manipulators in which the operator's motions are communicated directly to the

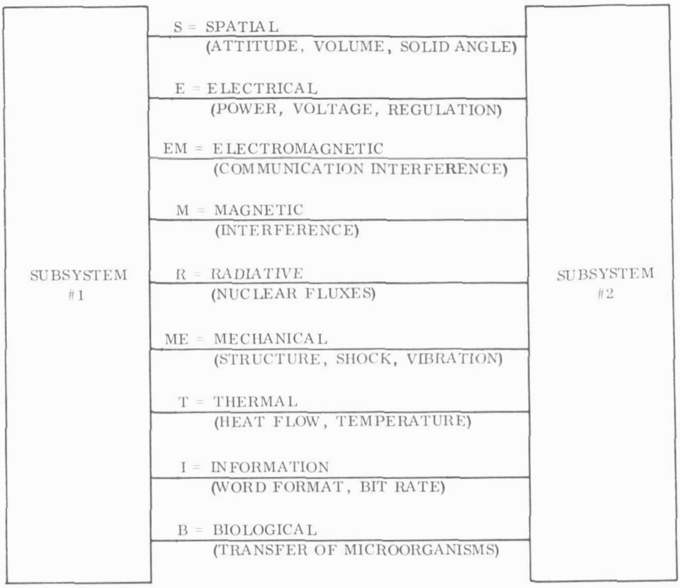

FIGURE 30.—Nine different kinds of interfaces exist between any two teleoperator subsystems. The actual importance of each kind of interface depends upon the subsystems involved. See fig. 29.

slave by cables and metal tapes. This interface does not exist in the electrical master-slaves.

While the necessity of matching electrical interfaces, such as voltage and current, with the power subsystem are manifest to all engineers, the *lingua franca* of the more advanced teleoperators is the *data word*. Subsystems converse among themselves by means of data words; the operator commands the actuators to perform dexterous operations with data words; the whole commerce of information exchange moves via the data word. The information interface is critical to successful intrasystem communication. Bit rate and word format, i.e., length, bit arrangement, etc., are highly important interface parameters.

Somewhere in the design process, interface specifications must be issued to all subsystem design groups; they are probably the most powerful tools promoting smooth hardware integration.

MAN-MACHINE INTEGRATION

The integration of man and machine is by far the most delicate, difficult, and least understood engineering task in teleoperator design. Interface specifications for hardware portions of the teleoperator are relatively simple to write down, but men are far more variable than manipulator arms or communications receivers. Who can accurately specify all of man's interfaces, particularly when it comes to perception and decision making? A start has been made, however, and this relatively new field is termed "human engineering" or "man-machine engineering."

The major man-machine interfaces occur in the control subsystem, where a man sees sensory data displayed before him and, in turn, dispatches commands to the rest of the teleoperator (fig. 31). The major data and command arteries fan out to the subsystems from the communication subsystem; but, in nearly every subsystem there are subtle and not-so-subtle short circuits where the human operator faces the machine squarely without intervening circuitry. The use of human-generated mechanical motion in mechanical master-slave manipulators and prostheses is only one of several "uninsulated" man-machine interfaces (illustrated schematically in fig. 31). Attitude disturbances caused by human motion in a satellite or submersible are another example. In a sense, then, a man may at times be considered an integral part of each and every subsystem. It is as part of the control subsystem, however, that his presence is felt most strongly in terms of teleoperator performance.

How can we best make a man feel at home as part of a teleoperator? Should we, as the old question goes, match man to the machine or the machine to man? A man well-matched to an anthropomorphic teleoperator can use skills learned in everyday living to operate the machine. Many of the tasks we wish to carry out with teleoperators, however, transcend human construction and may be performed best by nonanthropomorphic teleoperators. A homely example is unscrewing a nut; this is a quick and easy job for a manipulator hand with a rotary wrist but relatively hard for the non-rotating human hand, even with its 50-plus degrees of freedom. In current teleoperator language, there is little "compliance" between the human wrist and the nut-bolt task.

Existing teleoperators run the gamut from hula-hooping Handyman (fig. 32) to the many-jointed Serpentuator (fig. 33). Where quick reactions are required or where the operator is under stress, the more anthropomorphic controls are believed to be effective, although this is intuitive and unproven. The operator should not have to "think" about his actions in such instances. However, as the tasks to be performed become more specialized,

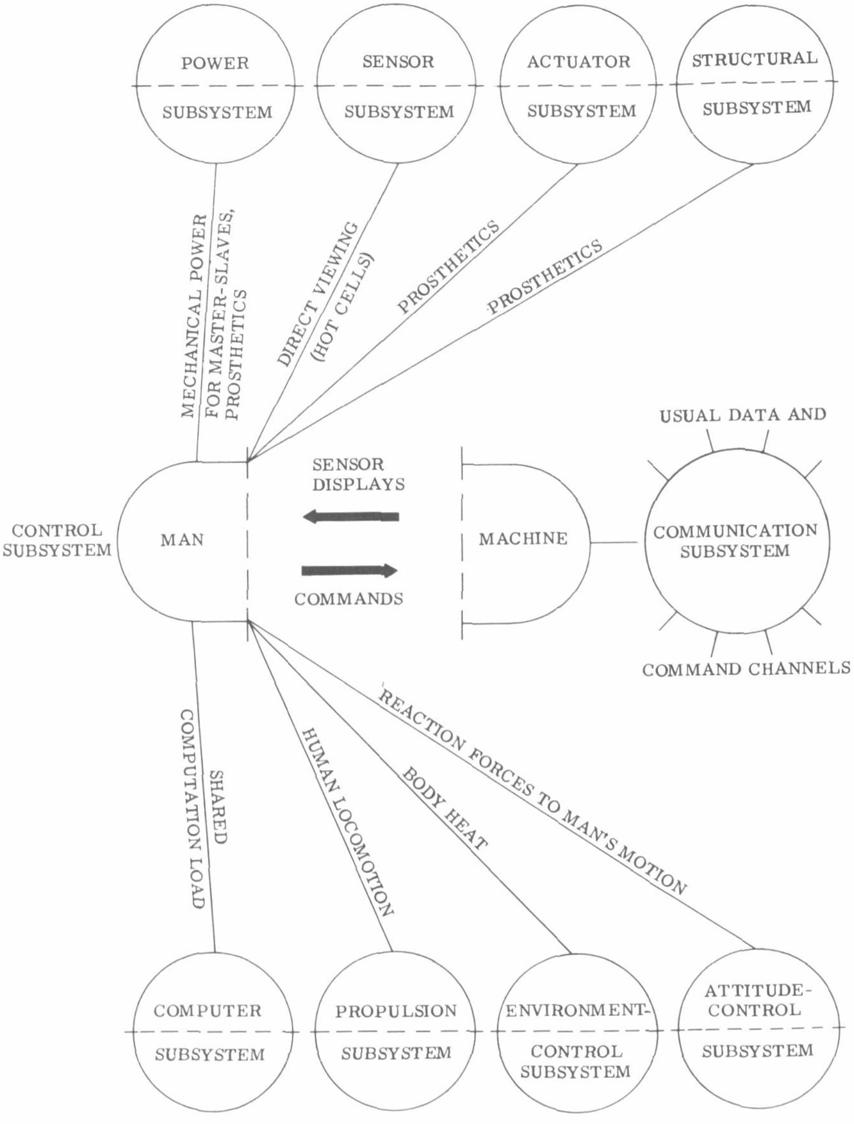

FIGURE 31.—In many instances, man effects subsystem operation directly without going through the communication subsystem.

the teleoperator is often more effective if it is dehumanized through specialized motions and controls.

A teleoperator can be made anthropomorphic by making the sensors simulate eyes and ears and the actuators like hands and feet. The General Electric Handyman exemplifies the anthropo-

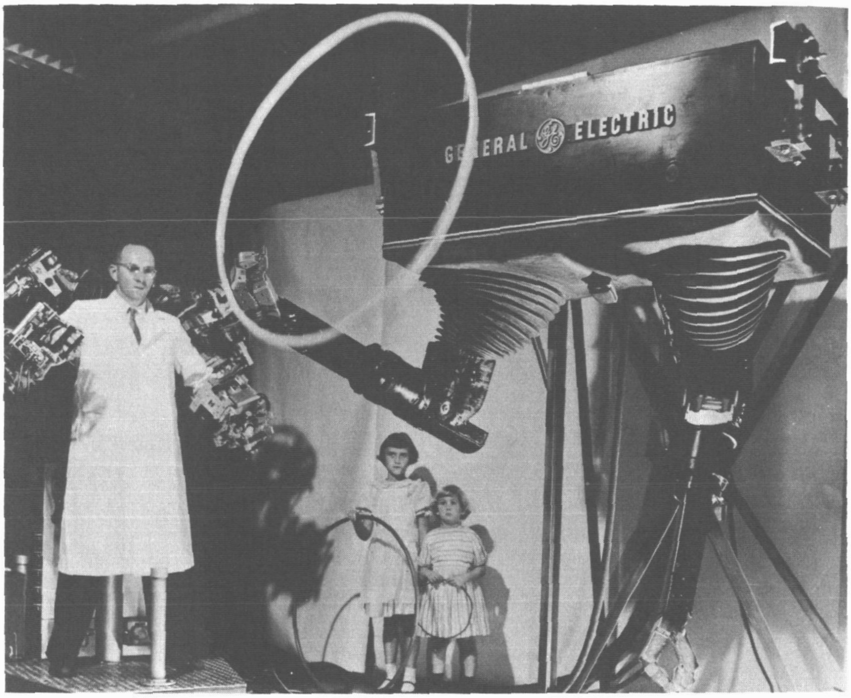

FIGURE 32.—The General Electric Handyman is a bilateral electrohydraulic master-slave. Built for the Aircraft Nuclear Propulsion (ANP) Program, it is shown here twirling a hula-hoop to demonstrate the degree of coordination possible between the master and slave arms in a bilateral manipulator. (Courtesy of R. S. Mosher, General Electric Co.)

morphic manipulator. There is direct visual contact with the operating space (a hot cell, for example), so that the operator-target distance is the only sensory factor notably different from those in normal working conditions. The Handyman actuators are human in character, though possessing fewer degrees of freedom. The exoskeletal controls fit right around the operator's body (fig. 32), resulting in a matching of anthropomorphic characteristics at input and output ends. Furthermore, there is "spatial correspondence;" a motion by the operator is duplicated exactly by the actuators in the operating space. The presence of force feedback completes a sensory picture that is not far different from that which the operator would encounter if he were in the hot cell handling the targets directly. Anthropomorphic teleoperators give the operator a better "sense of presence" or identification with the task being performed. It is usually easier for the operator to learn

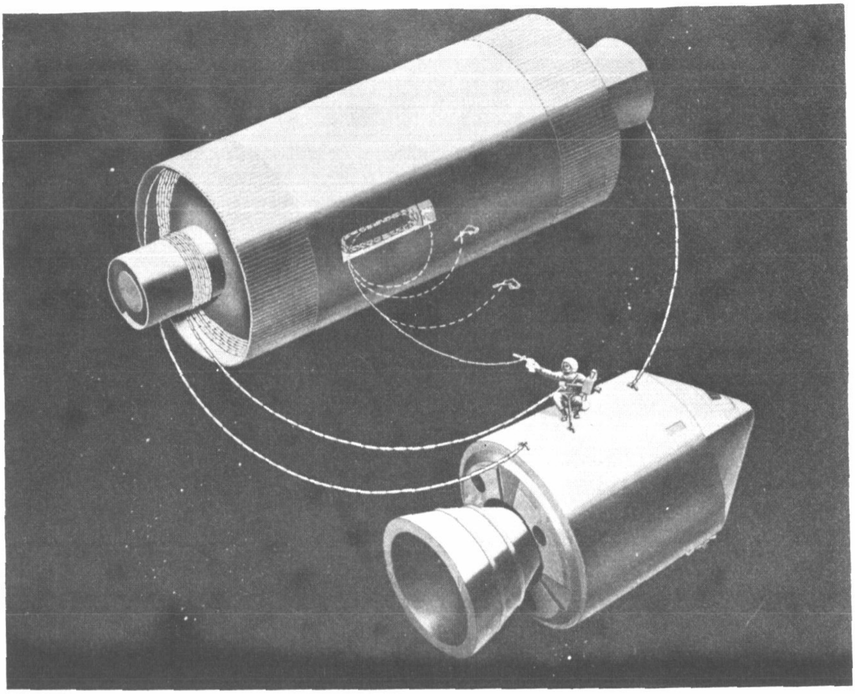

FIGURE 33.—The Serpentuator manipulator concept, showing arms used for tethering astronaut and space vehicle as well as transferring tools. (Courtesy of H. Wuenscher, Marshall Space Flight Center.)

and work with teleoperators that have been matched to him, rather than the inverse.

In the less anthropomorphic teleoperators, the Handyman control harness is replaced by a series of switches (figs. 34 and 35) to turn the actuator motors on and off. Unilateral manipulators operate from such switch controls. The joystick operator or control-panel operator watches the manipulator hand move toward the target as he closes and opens his switches. There is no force feedback as the motor-driven hand closes on the target. It is much like flying an airplane except that there is no seat-of-the-pants feedback, only visual information. Yet, without question, experienced operators of unilateral manipulators can project their presence into the operating space despite the nonanthropomorphic controls. The situation can be made even less anthropomorphic by replacing visual feedback with, say, a sonar display during underwater operations. As feedback data and commands become more and more foreign, the operator's effectiveness diminishes. Nevertheless, with training, the human brain can cope with many un-

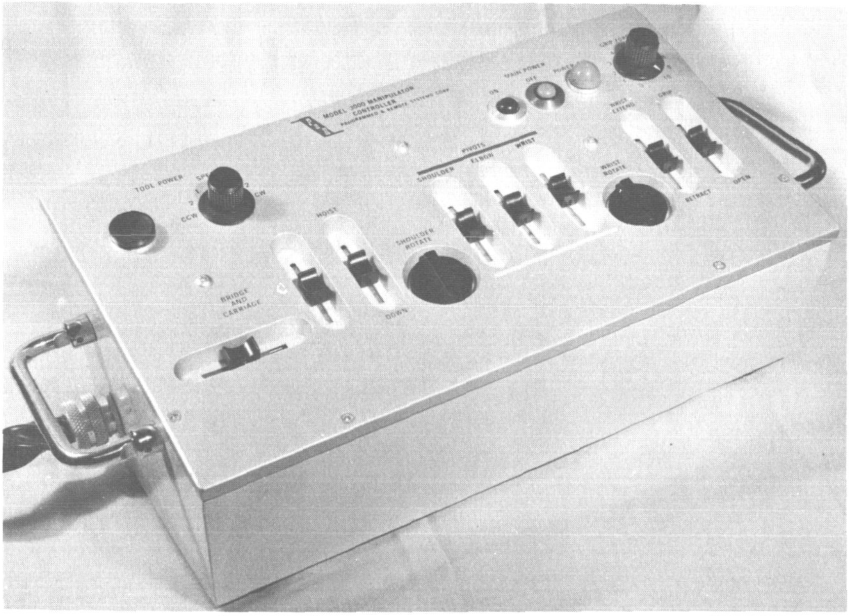

FIGURE 34.—Control box for the PaR Model-3000 unilateral manipulator. Contrast this switch-type control with the exoskeletal Handyman controls in fig. 32. (Courtesy of R. Karinen, Programmed and Remote Systems Corp.)

natural situations. To illustrate: a human wearing glasses that invert the visual world can learn to live in his upside down world with surprising ease. Humans also can adjust to nonanthropomorphic feedback displays and controls better than one might expect.

Assertions regarding the relative effectiveness of different teleoperators often imply that considerable experimental data exist, but no thorough studies have been made. The principal "task effectiveness" studies have come from the Aerospace Medical Research Laboratories at Wright-Patterson Air Force Base (ref. 35). In the last several years, different manipulators have been tested on standardized tasks and under different conditions. Perhaps the most significant single result to come from the Air Force studies is an objective measure of the extra cost—as measured in time to complete a task—of manipulators over direct handling. It took roughly six times longer to accomplish a simple manipulative task with a master-slave with the operator standing seven feet away than when the man did the job directly with his hands. At a distance of 11 feet, manipulators were at a 10:1 disadvantage. Of course, this cost in time is well worth it when a job can-

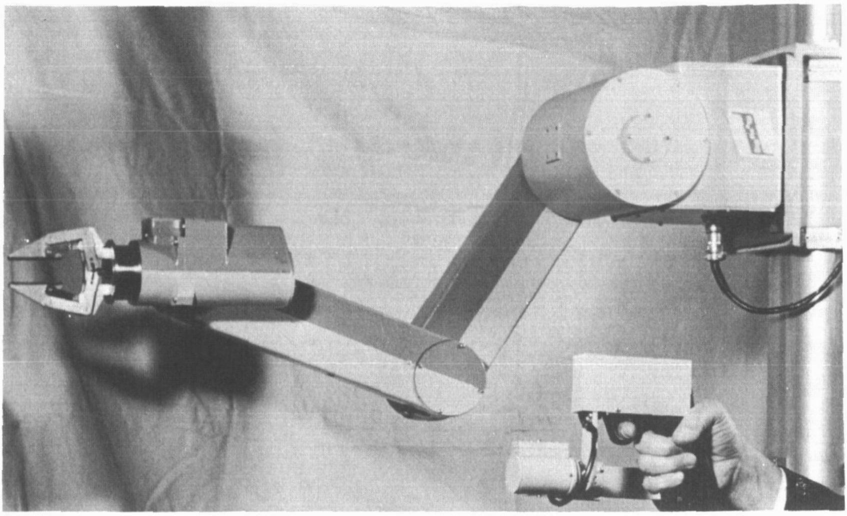

FIGURE 35.—A special joystick-like control for a unilateral manipulator. The operator's arm motions correspond more closely with those of the manipulator arm, making control more anthropomorphic than with the switches of fig. 34. Ordinary joysticks are similar to those used by pilots and are less closely related to manipulator motion. (Courtesy of R. Karinen, Programmed and Remote Systems Corp.)

not be done with the hands at all. The Air Force group also studied the effects of varying lighting and auditory conditions, color coding the manipulator jaws, and so on. Two additional results from these studies are pertinent here: (1) Contemporary three-dimensional television shows no particular advantages over two-dimensional television presumably because operators learn to use depth cues quickly, and three-dimensional TV is not well developed, and (2) joystick control is more effective for unilateral manipulators than the multiple switches used in the tests. Note that no task-effectiveness comparisons have been made between master-slaves and unilateral manipulators. In any such contest, of course, the identity of the winner would depend upon the nature of the task, particularly its degree of specialization, and the skills of the operators.

So far, the discussion has dealt with how far to go in molding the machine portion of the teleoperator to fit man. The other side to the story concerns picking and training men to join in man-machine symbiosis. Not just anyone will do.*

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*In the prosthetics field, of course, no opportunity for operator selection exists.

The operators should be selected with the same care as for jet pilots. Depth perception is obviously critical in using master-slaves through a hot-cell window or submersible porthole (ref. 36). Eye-hand coordination is a great asset in anthropomorphic master-slaves, especially when a slip can result in radioactive contamination or a similar catastrophe. Unilateral manipulators, however, are not affected so much by such coordination problems, although fast reaction time is desirable. Because most of today's teleoperators invade hostile environments, the human operator should display stability and resourcefulness in the face of environmental malevolence; viz., innate fear of nuclear radiation would not serve a hot-cell operator well, yet he should respect the forces at work. Good physical condition is also a prime requisite because, as mentioned above, it often takes ten times longer to do even simple tasks with manipulators. The dilettante thinks playing with manipulators is fun, much like running toy trains; but to the operator who makes his living at the end of a master-slave, it is hard, fatiguing, demanding work. Two hours standing in front of a hot-cell window, projecting one's gift for coordination through a thick window, is about all a man can take without a break. If the lighting is poor or the job far away, manipulation is even more fatiguing. Good manipulator operators are hard to find.

The most intimate of all man-machine relationships is found in prosthetic and orthotic devices. Here, every effort is made to shape the machine portion of the teleoperator system to resemble a normal man. An artificial arm should look like a real arm; the term for matching the external appearances of man and machine is "cosmesis." Of course, an artificial arm should also work like a real arm even though a nonanthropomorphic arm might be more effective for some purposes. The goal of most amputees or otherwise handicapped persons is normalcy; they do not want to stand out like a sore thumb. They want to take care of their personal needs quickly and without help. Hence the first requirement of the prosthesis designer is to make an artificial limb look real and perform realistically in everyday activities.

Proper matching of man and prosthesis cannot be all one-sided. The user must be trained in the care and use of his machine. The relationship is far more personal than that between a man and his car, although the same physical and psychological factors are present. An amputee may not choose the color and model of his prosthesis to gratify some inner urge as he does with a car, but he can learn to identify himself with an artificial limb and consider it a faithful extension of himself.

The control interface between a man and an artificial limb is usually unnatural in the sense that entirely new muscles have to be trained to provide limb motion. A shoulder muscle, for example, may be pressed into service through a special harness, to substitute for missing biceps. Or, if power is supplied externally (from perhaps a carbon-dioxide cylinder) the valves may be worked by an irrelevant set of muscles. Whatever the method of control, interface matching is difficult when the normal nerve fibers and muscles are gone or damaged.

A fascinating topic of current prosthetic research is myoelectric control (ref. 37). If a very tiny electrode is inserted into a muscle, a train of small voltage pulses can be picked up when the subject voluntarily commands the muscle to contract. EMG (electromyographic) pulses or spikes vary between 500 and 1,000 microseconds in width and may reach 25 millivolts in amplitude for a fine wire implanted in a single muscle fiber.* Surface or skin electrodes pick up larger and longer pulses from "motor units" consisting of many muscle fibers. Tiny electrodes implanted in a handicapped person's muscles may permit him to activate an externally powered artificial limb almost as easily as he would a real limb, especially if EMG signals from the original muscles can be tapped. Indeed, subjects can, with practice, voluntarily increase and decrease the EMG pulse frequency over a wide range. With the help of small solid-state control circuits and electric limb actuators, little-used muscles can be tapped as control-signal sources. Myoelectric control bridges the man-machine interface far more smoothly and naturally than uncomfortable, clumsy harnesses. As myoelectric control becomes better understood, it may supplement or replace hand- and foot-operated controls in other teleoperators with a normal, electrode-festooned operator at the helm. This would be just a step short of teleoperator thought control.

Between complex (and relatively undeveloped) myoelectric control at one end of the spectrum and simple but effective harnesses and master-slave controls at the other lie a surprising number of rather intriguing techniques by which humans can control machines. The least subtle are the human voice and motions of the human head. The head, in fact, is employed as a control device in the ANL TV2 television viewing system (fig. 36) (ref. 38). Electronic circuits can recognize spoken words and translate them into command signals for the teleoperator. Typical problems with this technique are the limited vocabulary possible

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*Electroneurographic signals from nerve fibers are about 1,000 times weaker.

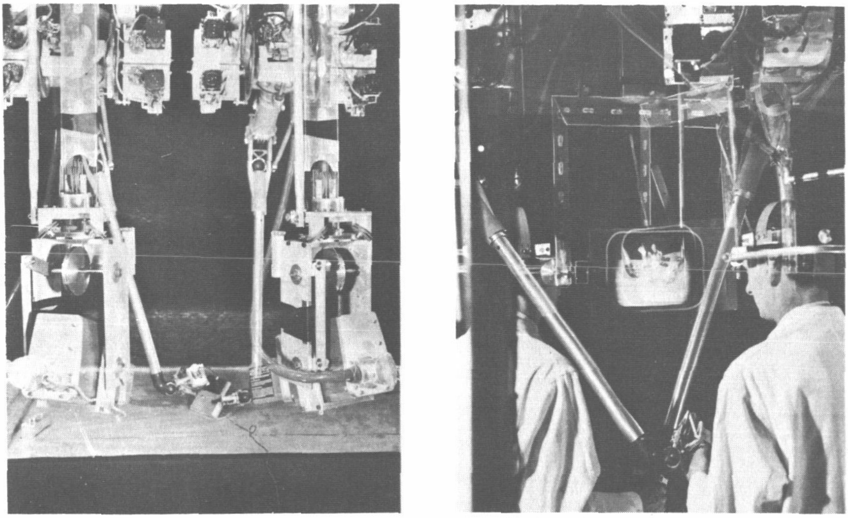


FIGURE 36.—Multiple-exposure photographs of the ANL head-controlled viewing system. The TV tube and camera (in the actuator space) both move as the operator's head moves. (Courtesy of Argonne National Laboratory.)

and variations in the spoken word from one operator to another. Other "oral" controls being investigated are voice tone, as distinguished from legitimate words, breath pulses, and even the tongue itself.

The human eye also has potential control utility. Because it is difficult physically to harness the human eye, the most popular eye control schemes pick up eye motion optically and convert the motion into electronically acceptable signals. The NASA eyesight switch control (fig. 37) depends upon the marked difference between the infrared reflection coefficient of the iris and 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 frame of the glasses detects the change in reflectivity. It is simply an eye-activated switch. More sophisticated eye-controlled devices are the gunsights that point aircraft armament in the direction a pilot's eyes are looking. Such equipment employs an optical system to follow some fixed region in the eyeball.

A human being evidently can generate a great variety of mechanical and electrical signals. Some are delicate, some coarse; some are suitable only for on-off control, others can control a tele-

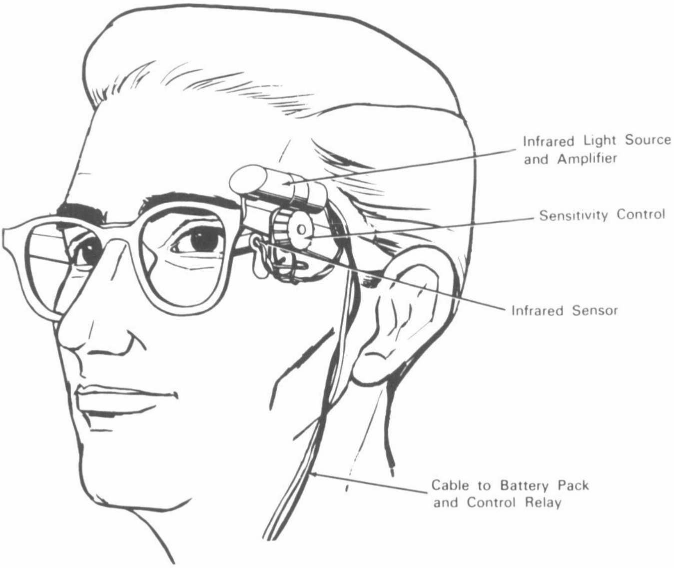


FIGURE 37.—Eyeball-controlled electrical switch. As the eye is voluntarily moved in the direction of the infrared sensor and light source, the eye's higher infrared reflectivity increases the sensor output sharply. (Adapted from NASA Tech Brief 65-10079.)

operator function continuously over a wide range. Most often, though, the hands and feet are the control links between man and machine because it is the very dexterity and sensitivity of these extremities that we wish to communicate to the teleoperator actuators.

The computer engineer frequently refers to devices that bridge the man-machine interface as input-output equipment. A computer printer, for example, is an output device that enables the computer to "talk" to the human operator. While computer people think primarily in terms of information in the abstract (words and bits) rather than mechanical motion of master-slave cables and EMG signals, any signal whether produced by hand, eyeball, or voice can carry information from a man to a machine. If these diverse kinds of information can be translated into computer language, man can be augmented substantially by that epitome of modern technology, the general purpose electronic computer. Happily, techniques have already been developed which convert various kinds of analog signals into digital language.

During computer augmentation of the teleoperator, the computer may merely help organize information in ways that facilitate human decision making and command generation, or it may partially or wholly replace man in making decisions and generating commands.

Sensor displays represent excellent examples of computer augmentation of information organization. To elaborate, an unmanned teleoperator exploring some dark ocean abyss may send back a sonar view of the environment plus signals indicating the positions of the target and the manipulator arms. If, say, for bandwidth reasons, television is impossible, the operator back aboard the control ship will have a difficult time unless these nonvisual signals are translated into a display that is physically similar to ocean-bottom actuality. A computer, knowing the dimensions of the manipulator arms and their telemetered configuration can draw them on a display screen for the operator. The target and environment can be superimposed to produce a realistic picture painted from nonanthropomorphic sensor data.

The use of computers in limited decision making and command generation has been termed "supervisory control" by Thomas B. Sheridan and his coworkers at Massachusetts Institute of Technology (refs. 39 and 40). Sheridan suggests that supervisory control may be useful in the following situations:

1. Where the response time of the teleoperator system is long because of signal transmission times (as in interplanetary exploration) and actuator sluggishness arising from large inertia, from low available actuating forces, and from resistance of the operating medium. Here, an on-the-spot computer may automatically prevent manipulator or vehicle damage resulting from collisions by processing local sensor data and overriding operator commands when necessary with nearly instantaneous local commands. Another example: if an object is slipping out of a manipulator hand, sensor data fed through the local computer may command the hand to grip the object tighter. In other words, a local, computer-operated control loop would be an extension of the human operator with built-in reflexes faster than those available through the main communication channel (fig. 38).
2. If bandwidth is limited on the main communication channel, a local computer can (a) compress data, (b) select the sensory data most important to current operations, and (c) automatically direct the sensors to focus on the most critical aspects of the situation at hand.
3. When a busy operator can use computer-stored subrou-

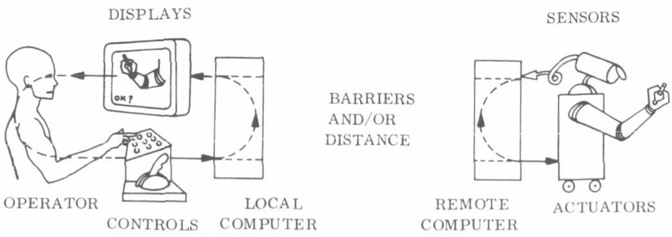


FIGURE 38.—In the M.I.T. concept of "supervisory control," the local and remote computers augment the human operator by carrying out subroutines, providing remote reflex action, and so on.

tines to handle routine operations (fig. 39). A computer may also flag critical developments for an operator inundated by data.

4. When a computer can recall previously unsuccessful manipulations to augment an operator's memory, particularly while he is under stress.

There are undoubtedly other ways in which computers can help integrate men and machines.

Of all the intricate facets of man-machine integration, the time-delay problem has intrigued scientists the most. Perhaps this interest is because of the peculiar sense of frustration and helplessness that time delays engender. Man evolved in a world where sound, sight, and touch feedback are nearly instantaneous, and the body is not equipped to cope with time delays. Public speakers become confused and inarticulate if they hear their own voices delayed by public-address-system acoustics. Handwriting becomes almost impossible if the writer sees what his hand is doing through a time-delay television presentation. Since teleoperator control represents a much higher level of man-machine coordination than either of these two simple examples, solutions are needed to help Earth-controlled teleoperators explore the Moon and distant planets. NASA has sponsored considerable research at Stanford University on the problems of driving remote vehicles (on the Moon for example) (refs. 41 and 42).

The block diagram in fig. 40 summarizes the physical picture. Command-transmission time delay occurs between the human controller and the distant actuators; a similar delay is experienced before the remote-sensor data is displayed before the operator. Human reaction time and delays in the electrical circuits must also be added to transmission delays. The net result is that the

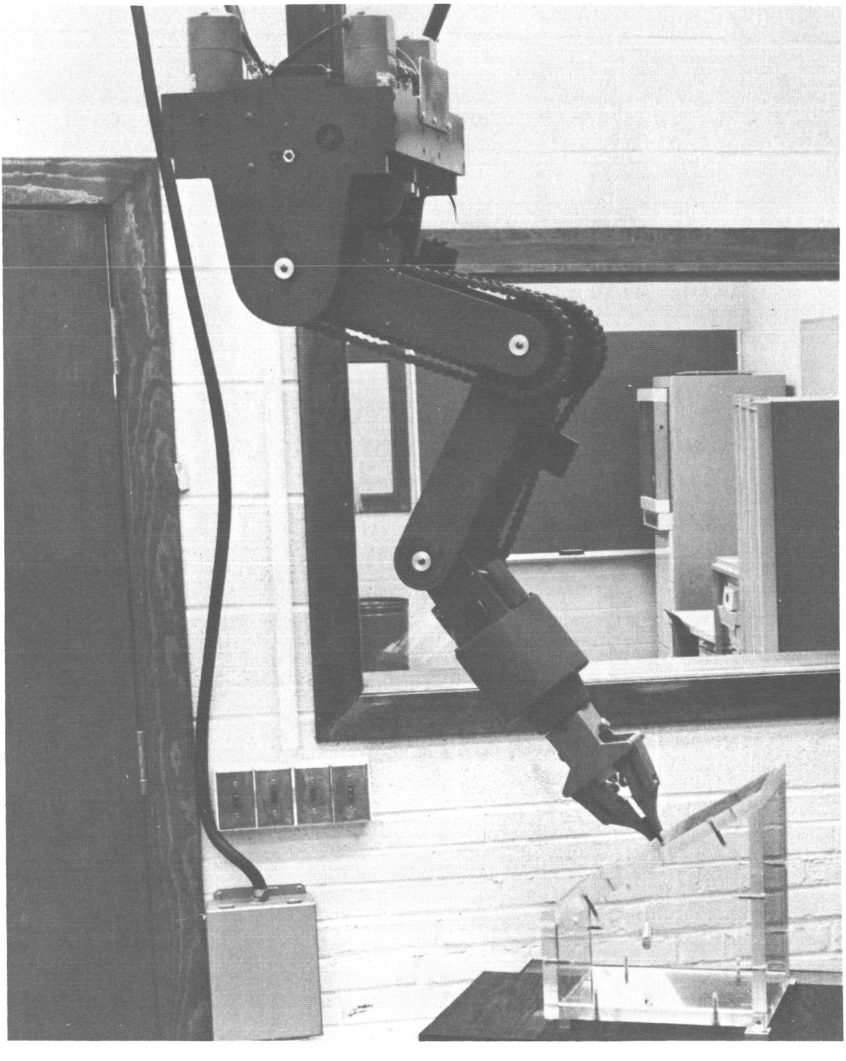


FIGURE 39.—This computer-controlled unilateral manipulator at Case Institute of Technology can carry out complex subroutines without operator assistance. (Courtesy of Case Institute of Technology.)

operator doesn't perceive the results of his actions until it may be too late to correct the situation.

The seriousness of the time-delay problem can be seen from fig. 41 (adapted from ref. 43), where three control regions are superimposed upon a solar-system distance chart. Low Earth-orbital missions fall within the first stable region, where time delays are less than a tenth of a second and the human operator

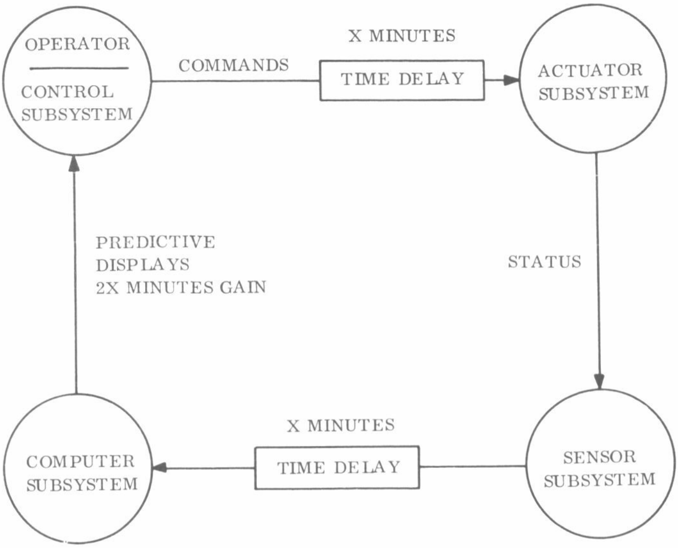


FIGURE 40.—In "preview control" a computer extrapolates actions in the actuator space and presents the operator with a "current" picture of activity. Time delays and advances around the loop add up to zero.

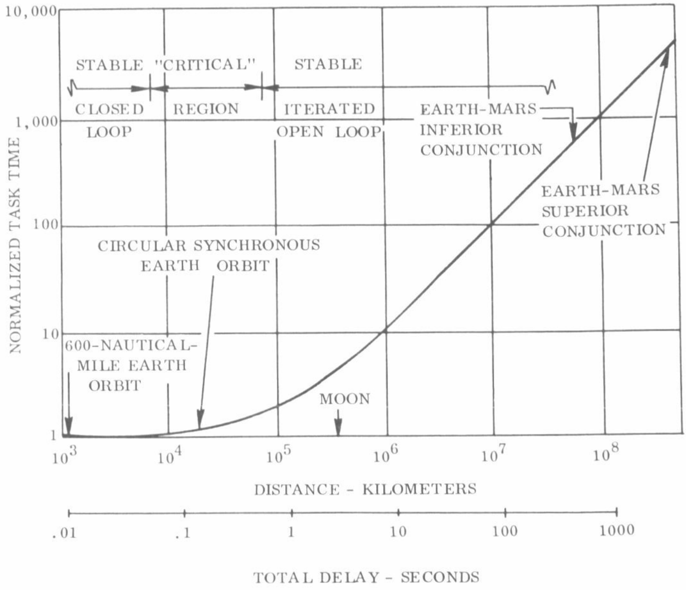


FIGURE 41.—Normalized task time vs. total time delay. A critical region where operator confusion is possible occurs in space missions at very high orbits. Move-and-wait operator strategy would be a successful but slow strategy for work on the Moon and planets.

can cope with them using natural, continuous, closed-loop control. When the total time delay is a few tenths of a second, the operator is torn between natural, continuous control and a move-and-wait, open-loop control philosophy. Operators find this situation emotionally upsetting, but stable control of teleoperators on the Moon and planets can be accomplished by a move-and-wait approach. Here, the operator moves a manipulator arm a bit and then waits to see the results of his action. W. R. Ferrell, at M.I.T., has conducted a number of experiments that demonstrate that most operators will quickly adopt this kind of control automatically (ref. 44). In this case, stability is purchased by the inefficient use of time—the round-trip time for radio signals in each move-and-wait cycle (six minutes for Mars).

In addition to system problems arising from operator confusion, further departures from stability can occur when the teleoperator is in a strong force field or attempting to handle fixed or heavy objects. NASA-sponsored research at M.I.T. by Sheridan and Ferrell has indicated that time delays may cause serious oscillations and great difficulty in maintaining target physical contact with the actuators (ref. 45). Sheridan and Ferrell point out further that the instabilities can be avoided by applying the feedback information to some other part of the body than the control hand (assuming this is how the operator accomplishes control). The use of signal lights to indicate the amount of force exerted on the target apparently interrupts the loop sufficiently to prevent oscillations.

Is there any way to use time more efficiently when operating a distant teleoperator? The use of a computer to generate displays extrapolated into the future is called "preview control." In essence, a computer digests sensor feedback, extrapolates it, and draws a television picture of the distant scene as it will appear one time-delay cycle away in time. The operator therefore sees the computer's guess at the future. Predicted results from any action he takes will show up *immediately* on the TV display, and he proceeds essentially in real time with closed-loop, continuous control. Of course, the computer's preview of the future may be in error, particularly if the time delays are long.

Preview control combined with supervisory control weld man, computer, and machine into a unit despite nature's tendency to split them apart with time delays and nonanthropomorphic information. The most interesting general observation resulting from this survey of man-machine problems is that the machine is almost invariably modified to fit man's idiosyncrasies and failings.

No one seriously suggests training operators to match difficult interfaces; emphasis is on fitting normal men with flexible, compliant machines.

CHAPTER 4

Teleoperator Design Principles

A design philosophy consists of general guidelines that summarize succinctly both hardware experience and theoretical expectations. It does not include specific performance goals, such as a particular lifting capability or level of power consumption. Rather, a design philosophy transcends specific missions, special applications, or a given type of teleoperator. A few important guidelines, however, will always be application-specific, such as the well-known admonition to use only radiation-resistant materials in hot-cell teleoperators. Finally, design philosophies are not hard-and-fast rules that have to be met with the rigor that engineers associate with design specifications; they are road signs, strategies, and distillations of experience. As such, they can be disregarded or modified at times, particularly when designing teleoperators for radically new environments or applications.

First, we will delineate those design philosophies that apply to all teleoperators and, after that, those few that are specific to the various application areas defined in chapter 2. The more important general design philosophies fall rather neatly into three categories:

1. Those that ease the burden on the human operator,
2. Those that make the teleoperator a more effective machine, and
3. Those that extend the teleoperator lifetime.

In the first category are such suggestions as:

1. The positions and velocities of teleoperator actuators should resemble those of the controls to help the operator project his presence into the actuator space. This is the well-known "principle of spatial correspondence." Most master-slave manipulators adhere closely to this philosophy, although controls on some space vehicles and submersibles may be scaled down in size to save volume. Even unilateral manipulator designers adopt the philosophy of spatial correspondence when they coordinate their switch and joystick controls with the manipulator

motions; i.e., pushing a switch left makes the manipulator arm swing left. Note that this principle applies to anthropomorphic and nonanthropomorphic teleoperators alike.

2. Teleoperator actuators should be modeled after man so that the operator will feel closely identified with the arms, hands, and fingers he is activating. (This question of anthropomorphic vs. nonanthropomorphic teleoperators was discussed in chapter 2.) At times, this philosophy can be waived to advantage. Most people, for example, feel at ease driving an automobile despite the non-anthropomorphic controls, actuators, and sensors. True, a car is not a teleoperator, but the illustration suggests that man is a more pliable component in the man-machine arrangement than is generally believed, and may not always have to be pampered.
3. Vision, force reflection (or "feel"), and all the environmental factors a human can sense should be incorporated into teleoperator design. The objective of "sensory correspondence" is also to enhance the operator's identification with the task at hand. Contemporary teleoperators rely primarily on vision, because the cost of adding sound and feel may not be commensurate with the improved effectiveness of the teleoperator. Sensory correspondence, like all other design factors, must be balanced against other desirables.
4. Teleoperator controls should not be "spongy" or sluggish, yet they should not be so sensitive that the operator's least tremor is communicated to the actuators. The automobile analogy is apt again—the steering wheel should have a little but not too much "play" in it. Drift must be negligible, too. Force feedback in the teleoperator should be clean and crisp but not so strong that it tires the operator. (Mechanical and electrical force multiplication can reduce force feedback to tolerable levels.)
5. The visual scene communicated to the operator should be immobilized; that is, spatially fixed. As the operator turns his head, he should see a different portion of the environment. We could call this "visual correspondence" and define it as a partial union of sensory and spatial correspondence. It means more than merely a faithful, picture-like reproduction of the scene in the operating space. Today, only head-controlled television sets and large windows can create visual correspondence.

6. Actuators and optical sensors should not mutually interfere; that is, the manipulator hands should not obscure the operator's view of the object that he is manipulating.
7. All actuator degrees of freedom (joints, wrist extensions, etc.) should be designed to move continuously and simultaneously, without excessive backlash, much like the operator moves his limbs and digits. It is tempting to add that there should be no cross coupling between different degrees of freedom; viz., movement of joint X does not cause some motion of joint Y as well. This, strangely enough, would be a nonanthropomorphic requirement because human tendons are often "cross-coupled." Zero cross coupling makes control theory simpler, but it is not always essential to good hardware design.

In the second category of design philosophies are those that make the teleoperator more useful or effective.

8. Teleoperator design should be kept "generalized" as far as possible. Biologists maintain that the human being is successful among the animals because his brain, limbs (excluding the feet), hands, and other "subsystems" can perform many different functions; i.e., they are unspecialized. Since teleoperators are extensions of man, they will be of greatest general value if specialization is avoided.
9. The actuators should exhibit "compliance" or compatibility in degrees of freedom with the motions making up the mission. If the job involves rotary motion, such as turning bolts, rectilinear manipulators are seldom desirable. Compliance means matching the teleoperator to the job. Compliance, rather obviously, implies specialization of teleoperator design, contradicting the preceding design suggestion. Such conflicts are inevitable in engineering any complex system. Trade-off studies must be made to determine what mix of compliance and generalization yields the highest performance over the expected application spectrum.

The third and final group of philosophies includes those that help the teleoperator survive the rigors of use and environment.

10. Teleoperator design should be clean and simple, with the most critical components parallel to encourage high reliability. This sounds like an unnecessary hortatory

remark, but reliability cannot be overemphasized in environments where recovery and repair are difficult or impossible.

11. Self-repair capability should be built into a teleoperator that cannot be repaired by man directly. Most teleoperators have arms and hands backed by human operators. With this dexterity and resourcefulness available, defunct parts can be replaced if spares and proper tools are within reach of the manipulator hands. The teleoperator should be designed with an eye to easy disassembly and repair by its own arms and hands. In effect, this means that the manipulator arms should be able to reach all repairable components, and that the viewing system should be adjustable to make the teleoperator introspective. Two manipulator arms are particularly useful in self-repair situations.
12. Closely associated with self-repair is the "modular" concept, wherein the teleoperator is constructed from easily replaceable building blocks. Maintenance and self-repair are easier then and improved components can be installed when developed; viz., more powerful or longer arms.
13. The teleoperator should be provided with a stable environment insofar as possible. Temperatures, the internal atmosphere, vibration loads, and so on, must be controlled carefully if long life is desired. In practice, this idea is translated into environment and interface specifications that are consistent with known lifetime characteristics of the teleoperator components. Unfortunately, little reliability data is available on teleoperator components.
14. The teleoperator actuator subsystem should be provided with proximity and limit switches as well as stress-limiting devices, such as slip clutches and pressure valves. With some foresight, the designer can prevent teleoperator damage that might otherwise be incurred in trying to lift or move overweight objects, or by collisions among its own parts and the targets being handled.

Some of the more important specialized guidelines are summarized by application area in table 4.

Concluding this section is a second table wherein the ten teleoperator subsystems are cross-indexed with the eleven important application areas. Table 5 is a preview of the rest of this chapter as well as chapters 5 and 6; it summarizes key subsystems.

TABLE 4.—*Application-Specific Design Philosophies.*

Application area	Design philosophy
Aerospace	Teleoperator-bearing space vehicles should be attached and anchored firmly to the target to preclude excessive attitude perturbations. Local computers should be incorporated in teleoperators on lunar and deep-space missions to provide supervisory control (see chapter 3). Preview control or its equivalent should be employed in planetary teleoperators to overcome time-delay problems (see chapter 3). Low weight and power consumption, and high reliability are critical.
Undersea	Teleoperator attachment and anchoring are required, as described above. Materials should be compatible with seawater.
Nuclear	Teleoperator components in the actuator space must be radiation-resistant. Hydraulic manipulators should be avoided in hot cells because of the great difficulty in cleaning up oil leakage. Low cost is a critical factor in commercial application.
Terrestrial transportation and materiel handling	Low cost is important because of competition with helicopters and wheeled vehicles. Gaits that annoy or sicken the operator must be avoided.
Medical	Prostheses must "look right." Low cost is essential for prostheses. Equipment for surgery must be able to withstand sterilization. Low weight and power consumption are essential.
Chemistry and biology	Teleoperator actuators must be able to withstand repeated cleaning and, in some cases, sterilization. Precision motion is desirable.
Public service	Low cost is an important factor because of the competition of conventional equipment. Rugged construction is essential.
Entertainment	Operator concealment is often an important factor.

The manipulators, which are often man-like, and the sensory organs that attempt to duplicate the scene a man would see if he could occupy the actuator space, often are so critical to the success of a teleoperator that a full chapter has been assigned to each; these are chapters 5 and 6. The other eight subsystems represented in fig. 29 will be discussed in this chapter.

THE CONTROL SUBSYSTEM

In examining the control subsystem, one should remember that teleoperator commands need not be carried solely by electrical and

TABLE 5.—*Comparison of Teleoperator Subsystem Features by Application Area.*

Application area	Actuator subsystem
Aerospace	Electrical master-slaves will probably be best in space. Mechanical master-slaves now used in terrestrial test chambers.
Undersea	Electrohydraulic and electric unilateral manipulators now dominant.
Nuclear	Mechanical master-slaves abundant; electrical master-slaves at ANL. Electrical unilateral manipulators commonly used in very large hot cells and on vehicles.
Terrestrial transportation and materiel handling	Walking machines will usually have more than two legs because of the stability requirement. Unilateral actuators for military use. Man amplifiers will probably be hydraulic and electrohydraulic.
Medical	Wide array of limbs, hands, and ingenious joints and linkages now available.
Chemistry and biology	Mechanical master-slaves dominant.
Metal industry	Heavy-duty hydraulic unilateral manipulators used almost exclusively.
Electronics	Mechanical and electrical unilateral and master-slave manipulators will probably be employed.
Construction and mining	Heavy-duty hydraulic unilateral manipulators used extensively.
Public service	Unilateral manipulators probably will dominate this field.
Entertainment	Both mechanical master-slaves and electrical unilateral devices will probably be used.

TABLE 5.—*Comparison of Teleoperator Subsystem Features by Application Area.*—Continued

Application area	Sensor subsystem	Control subsystem
Aerospace	Direct viewing can be used in orbital work; TV for lunar and planetary work; force reflection likely in both applications. Direct vision in terrestrial test chambers.	Closed-loop tracking by operator likely in orbit. Preview display and supervisory control for distant planets. Open-loop control reasonable out to Moon.
Undersea	Direct viewing from submersibles. TV for unmanned exploratory craft and rescue vehicles. Sonic imagers may find use where vision is difficult.	Open and closed-loop operator tracking used. Miniaturized electrohydraulic position controllers becoming common. Switches and joysticks for the now-dominant unilateral manipulators.
Nuclear	Direct vision and force feedback dominant in hot-cell work. TV employed on mobile equipment and in large hot cells. Microphone pickups common.	Open and closed-loop operator tracking. Switches, joysticks, master-slaves, exoskeletal control devices.
Terrestrial transportation and materiel handling	Direct vision.	Closed-loop, operator-tracking. Exoskeletal controls. Subroutines for easy terrain.
Medical	Direct vision for prosthetics. TV for remote surgery inescapable.	Closed-loop, operator tracking. Various body-operated switches and exoskeletal controls. Myoelectric control under development.
Chemistry and biology	Direct vision.	Closed-loop, operator tracking. Master-slave controls.
Metal industry	Direct vision.	Closed-loop, operator tracking. Switch controls.
Electronics	Direct vision.	Closed-loop, operator tracking supplemented by subroutines. Switch controls.

TABLE 5.—*Comparison of Teleoperator Subsystem Features by Application Area.*—Continued

Application area	Sensor subsystem	Control subsystem
Construction and mining	TV.	Closed-loop, operator tracking. Switch controls.
Public service	Direct vision supplemented by TV for mobile equipment likely.	Closed-loop, operator tracking. Switch controls.
Entertainment	Direct vision.	Closed-loop, operator tracking, supplemented by subroutines. Exoskeletal controls.

Application area	Communication subsystem	Computer subsystem
Aerospace	Electromagnetic links for distant teleoperators inescapable. Hardwire links for orbital manned work capsules. Mechanical manipulators for test-chamber work.	Digital computers may be employed in local preview control, in distant supervisory control, and in data compression.
Undersea	Hardwire links, including trailing vehicular cables, are most common. Acoustic links possible.	Digital computers may be used for distant supervisory control, and in data compression.
Nuclear	Mechanical links dominate in master-slave type of manipulators. Cable and radio-controlled vehicles exist.	None.
Terrestrial transportation and materiel handling	Hardwire links for unilateral manipulators.	None.
Medical	Mechanical and hardwire links in prostheses.	None.
Chemistry and biology	Mechanical links.	None.
Metal industry	Hydraulic links most common.	None.
Electronics	Hydraulic and hardwire links.	None.

TABLE 5.—*Comparison of Teleoperator Subsystem Features by Application Area.*—Continued

Application area	Communication subsystem	Computer subsystem
Construction and mining	Hydraulic links for manned machines. Radio and hardwire links for vehicles.	None.
Public service	Hardwire links.	None.
Entertainment	Acoustic, mechanical, radio, and hardwire links.	None.

Application area	Propulsion subsystem	Power subsystem
Aerospace	Reaction engines (chemical or cold gas) for space. Walkers and wheels for planetary surfaces.	Chemical APU's, fuel cells, solar cells; nuclear power in the future.
Undersea	Screws and jets now used in submersibles. Tracks for bottom crawlers.	Batteries, chemical APU's, nuclear power plants, and electric lines now in use.
Nuclear	Bridge-crane-type carriages. Tracks used for most vehicular manipulators; wheels on a few. Walkers possible in future.	Human-powered master-slaves, electric lines, chemical engines (gasoline, Diesel), all in use.
Terrestrial transportation and materiel handling	Walking machines likely.	Chemical engines (gasoline, Diesel, gas turbines) for future walking machines and exoskeletons.
Medical	Only walking machines and artificial legs considered.	Human power, compressed gas, batteries now in use.
Chemistry and biology	None.	Human-powered master-slaves used.
Metal industry	Heavy tracked or wheeled vehicles.	Chemical engines (gasoline, Diesel).
Electronics	None.	Human-powered master-slaves, electric lines.
Construction and mining	Heavy tracked and wheeled vehicles.	Chemical (gasoline, Diesel).

TABLE 5.—*Comparison of Teleoperator Subsystem Features by Application Area.*—Continued

Application area	Propulsion subsystem	Power subsystem
Public service	Heavy tracked and wheeled vehicles.	Chemical (gasoline, Diesel).
Entertainment	Walking machines. Some wheeled vehicles.	Human power, electric lines.

Application area	Vehicle attitude-control subsystem	Environment-control subsystem
Aerospace	Cold and hot-gas jets, docking arms, and gyros will probably be employed.	Active (moving) and passive radiators; subliming and evaporating materials; various heat sinks and various life-support systems have all been proposed. Meteoroid and radiation shields.
Undersea	Screws now. Motion of operator and/or fluids inside submersible used to some extent. Docking arms potentially useful.	Seawater heat sinks. Various life-support systems.
Nuclear	None.	Vehicle radiators. Radiation shielding.
Terrestrial transportation and materiel handling	Walking-machine legs stabilize operator.	Vehicle radiators. Armor in warfare.
Medical	None.	None.
Chemistry and biology	None.	None.
Metal industry	None.	Vehicle radiators.
Electronics	None.	None.
Construction and mining	None.	Vehicle radiators.
Public service	None.	Vehicle radiators.
Entertainment	None.	None.

TABLE 5.—*Comparison of Teleoperator Subsystem Features by Application Area.*—Concluded

Application area	Structure subsystem	
Aerospace	Space capsules proposed for manned orbital systems. Open frames and polygonal shells suggested for unmanned vehicles.	
Undersea	Massive hulls to withstand extreme pressures. Open frames for unmanned vehicles.	
Nuclear	Master-slaves suspended from central supports. Column and wall-mounted unilateral manipulators.	
Terrestrial transportation and materiel handling	Exoskeletons, legged platforms proposed.	
Medical	Artificial limbs with internal or external skeletons.	
Chemistry and biology	Master-slaves suspended from horizontal support.	
Metal industry	Truck/tank structures.	
Electronics	Master-slaves suspended from horizontal support.	
Construction and mining	Truck/tank structures.	
Public service	Truck/tank structures. Legged platforms.	
Entertainment	"Internal" skeletons.	

electromagnetic (radio and laser) signals. Mechanical communication linkages are, in fact, more common in extant teleoperators. Signals may also travel via hydraulic and pneumatic links.

In driving an automobile, a man encounters many problems common to all man-machine systems. Using direct vision, he "tracks" the road with the car. On the basis of visual, kinesthetic (inertial) forces, and audio feedback, the driver manipulates the steering wheel, the accelerator, and gear shift, as well as lesser equipment, such as the horn and windshield wipers. Yet, many of us do all this almost without thinking. The overall teleoperator control loop (fig. 42) serves equally well for automobile driving and for a teleoperator.

The essence of control is the issuance of crisp, effective commands that quickly achieve the desired objective, whether it is loading fuel pellets in a fuel rod or remotely repairing a satellite. The teleoperator control subsystem—including its most important component, man—may receive a wide spectrum of feedback signals via the communication subsystem, compare the signals with the desired objective, and issue new commands via the communication subsystem.

(This section discusses only the left-hand portion of fig. 42. The navigation and guidance of spacecraft and submersibles, particularly during rendezvous and docking, are beyond the scope of this book.)

In control theory, the "loop" is the thing. Teleoperator control loops are commonly termed "closed" when the operator receives some kind of feedback *other than visual* that tells him how well he is accomplishing the task at hand. Commands, feedback, and corrected commands usually flow continuously. But it is not always so; in time-delayed feedback a move-and-wait strategy can be effective. Moving a teleoperator control in the absence of feedback is like switching on a light; the act is done before errors can be corrected. Ultimately, delayed feedback signals may tell the operator the consequences of his action, but not soon enough to prevent disasters or to take advantage of timely opportunities.

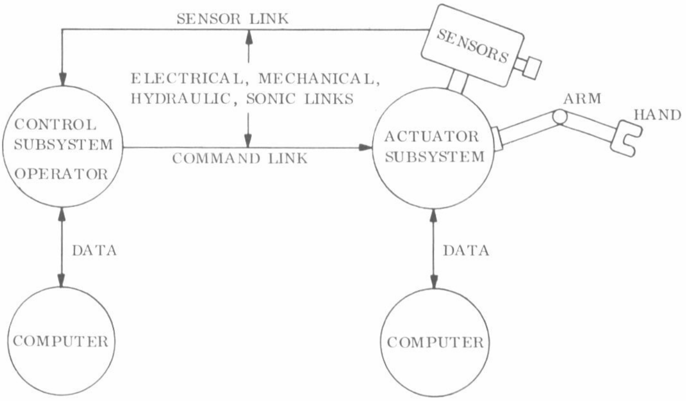
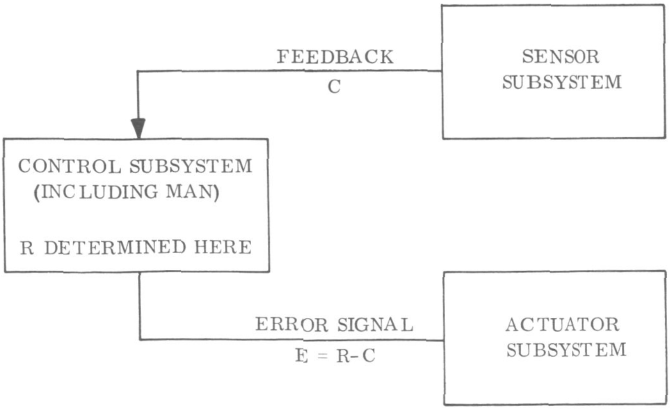


FIGURE 42.—Command and sensor communication links tie the actuator and control subsystems together. All links carrying information are part of the communication subsystem.

A simple theoretical exposition will contrast open- and closed-loop systems as well as provide some insight into control-system mathematics. In the block diagram of fig. 43, the controlled quantity C might represent one of the many degrees of freedom possessed by a master-slave manipulator, say, the vertical distance of the hand above the plane of the target. The hot-cell operator knows where he wants the hand to be, R, and automatically computes the error, $E = R - C$. To eliminate ("null") the error, he generates a command proportional to the error, HE, where H includes the so-called "human transfer function." The resulting command M_1 is transmitted to the actuators. The actuators see the command M_1 as modified by their own transfer function, G, and also a "load" signal, M_2 (viz., some environmental disturbance at the manipulator hand). The controlled variable is then given by: $C = G_1M_1 + G_2M_2$, for simple linear control systems. Since $M_1 = HE$, the expression for the error signal is:

$$E = \frac{R - G_2M_2}{1 + HG_1}$$

Of course, the operator does not use this equation consciously; all his control motions are made automatically. Usually, he can handle



C = ACTUAL VALUE OF CONTROLLED QUANTITY
R = DESIRED VALUE OF CONTROLLED QUANTITY
E = ERROR SIGNAL

FIGURE 43.—Block diagram of a feedback control subsystem.

dozens of different degrees of freedom simultaneously if the controls and actuators are anthropomorphic. After all, a human arm and hand have dozens of degrees of freedom between them, and a normal person experiences no difficulty in controlling most of them continuously and simultaneously.

Several characteristics of linear control loops are obvious from an examination of the above equation:

1. Zero error can be attained only if $HG_1 = \infty$.
2. An infinite error results if $HG_1 = -1$.
3. The possibility of oscillatory behavior exists if the corrective signals are phased so as to reinforce the error signals.
4. The control of the entire teleoperator depends upon proper matching of the interfaces among the control, actuator, and communication subsystems. The equation for E, above, ties them all together for one degree of freedom.

The function of the control subsystem in the light of this elementary discussion is the rapid reduction of the error signals to acceptable values without the introduction of instability (oscillations). Damping forces and circuit gain adjustments are useful in attaining this goal.

With a human in the control loop, further analysis becomes most difficult because the human transfer function, inherent in H, is almost an unknown factor. However, the simple model given above is a convenient framework for subsequent discussion. For further theoretical development of the subject, the extensive literature should be consulted (refs. 46 and 47).

The human operator commands the teleoperator through a system of controls that he usually, but not always, manipulates with his hands. The controls may be handles, levers, or buttons with which he gains access to the machine. (Where a specific type of control system is particularly significant to the development of teleoperators, a hardware example will be given.)

Table 6 lists input control devices either in common use today or under intense development. The error signal in almost every instance is the difference between actual and desired manipulator positions. This is the usual situation when dealing with fixed objects. If, however, an operator were trying to catch a moving object with a manipulator, he would try to match velocity and acceleration as well as position. This is the "tracking" problem; it does not arise in teleoperator design for applications involving fixed targets.

Most unilateral manipulators are termed "rate" or "velocity" controlled because they are usually driven at speeds determined

TABLE 6.—*Common Input Control Devices.*

Error signal*	Parameters controlled	Control devices
Position difference	Velocity (constant) (unilateral manipulators)	Switches (also called "control arrays") Joysticks Myoelectric signals Eye, head, shoulder, etc.
Position difference	Velocity (proportional) (unilateral manipulators)	Potentiometers Joysticks Myoelectric signals
Position difference	Position/velocity/ acceleration	Position controllers (PaR type) Replica or model controllers (also called servo controllers)
Position and force differences	Position/velocity/ acceleration/force (master-slave manipulators)	Mechanical, electrical, or hydraulic force-reflecting, master-slave input hands, arms, etc. Exoskeletons (really variations of the master-slave) Prosthesis harnesses (related in principle to mechanical master-slave)

*Acoustic and proximity indicators are occasionally used with today's manipulators, but the information they transmit is generally of an "alarm" nature and is not used in normal operation.

by the operator. Master-slave manipulators are called "position" controlled because the error signal is usually one of position. Force, velocity, and acceleration seem to fade into the mind's background as one moves the master arms in response to position-error information seen through a hot-cell window or on a television screen.

A switch-controlled unilateral manipulator (at the top of the right-hand column in table 6) is simplicity itself. When an operator wishes the wrist joint of the manipulator arm (on the screen in fig. 44) to turn counterclockwise he moves the appropriate switch left; the circuit is completed, and a motor rotates the wrist accordingly. As the target is approached, the wrist eases up to it through a series of small increments commanded by the operator and the switch. Most modern unilateral manipulators, however, are controlled by potentiometers. With dc actuator motors powered by magnetic amplifiers, potentiometers provide variable speed control. Manipulation is thus carried out more smoothly and naturally with less chance of collision (ref. 48). This discussion also applies to hydraulic unilateral manipulators, such as those employed in handling hot, heavy forgings. In this instance, a valve substitutes for the electrical switch and a hydraulic actuator drives the manipulator.

Switch controls have two disadvantages: (1) There is usually rather poor correspondence between switch movements and those of the manipulator and (2) the operator occasionally has to take his eyes off the work to make sure which switches he is activating—no matter how adept he becomes at touch control. Sometimes expensive and fragile objects are inadvertently dropped in the process.

These difficulties have led to the development of manipulator joysticks, which combine all or most of the switches on a single control (fig. 45). The integration of the switches into a single, hand-sized control permits an operator to concentrate on his work instead of his switches. Furthermore, joystick structure and

FIGURE 44.—The MOBOT control panel. The MOBOT is a vehicle with two unilateral, switch-actuated, electric manipulators. The console also contains controls for the two MOBOT television cameras. (Courtesy of Hughes Aircraft Co.)

motions can be made to simulate those of the manipulator being controlled, thus improving the man-machine interface. Crawford has reported task effectiveness studies in which the joystick was demonstrably superior to a panel of switches (ref. 49). The Position Controller built by Programmed and Remote Systems, Inc. (fig. 35)* is in this category. With a properly designed joystick, the unilateral manipulator becomes almost as proficient as the master-slave at drawing circles and swinging hula-hoops. Limiting factors are backlash and motor speeds.

So far, the discussion has been oriented toward the control of manipulators by normal people. Powered prosthetic devices are also commanded by switches although they are intentionally less obvious than a control panel. Concealed microswitches activated by muscle bulges are common. Eye motion, head motion, and many other bodily movements can also be tapped as switch closers. Electromyographic (EMG) signal patterns can be recognized by electronic circuitry as a switch-closing signal. Experimental EMG-controlled artificial limbs have been built and tried, especially in Europe.

Unilateral teleoperator control subsystems that use switches and joysticks are easy to render in hardware form; but, except for visual feedback signals, there are no feedback loops that enable the teleoperator to "home" on a commanded "state" or configuration of manipulator arms and hands. Unilateral manipulators are conventionally labeled "open loop," even though the operator does, in effect, close the loop by watching the manipulator motion and continuously correcting it with his switches, potentiometers, or joystick. The term "closed-loop" is generally reserved for those teleoperators in which the control loop can be closed *without* the aid of the eyes of the human operator; that is, an error signal can be nulled independently of visual cues.

There are actually few closed-loop teleoperators that do *not* include force reflection (or feedback) as part of their sensory repertoire. Also common is the so-called "position servo controller," sometimes called a "model" or "replica" controller. The basic idea involves the construction of a small-scale model of the manipulator (fig. 46). The joints of the manipulator and its model both have electrical pickoffs (potentiometers) that provide the control system with two signals that it tries to equalize by driving the manipulator joint motors (fig. 47).

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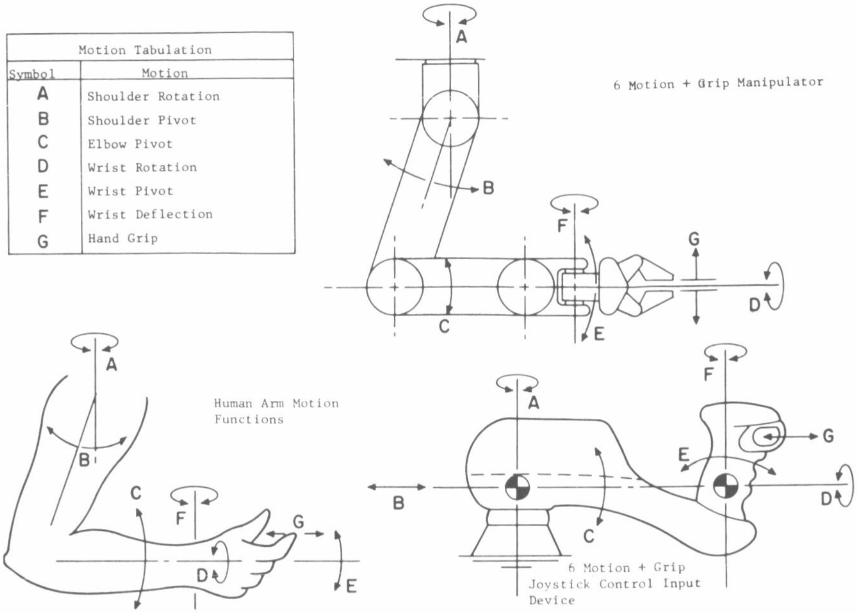
*With the PaR Position Controller, the *motion* of the Controller establishes the direction and rate of the manipulator motion, whereas in normal joystick control it is the *position* of the joystick that determines direction and rate.



Motion Tabulation	
Symbol	Motion
A	Shoulder Rotation
B	Shoulder Pivot
C	Elbow Pivot
D	Wrist Rotation
E	Wrist Pivot
F	Wrist Deflection
G	Hand Grip

FIGURE 45.—Three drawings showing the parallelisms between the operator arm, the joystick, and the remote manipulator. Despite the anthropomorphic character of the joystick, the manipulator is classified as "unilateral." (Adapted from ref. 59.)

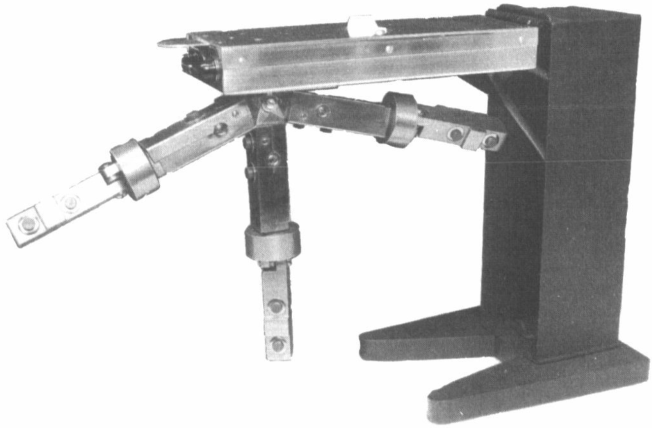


FIGURE 46.—A position-servo or "scale-model" control arm designed for underseas manipulators. (Courtesy of Electric Boat Division, General Dynamics Corp.)

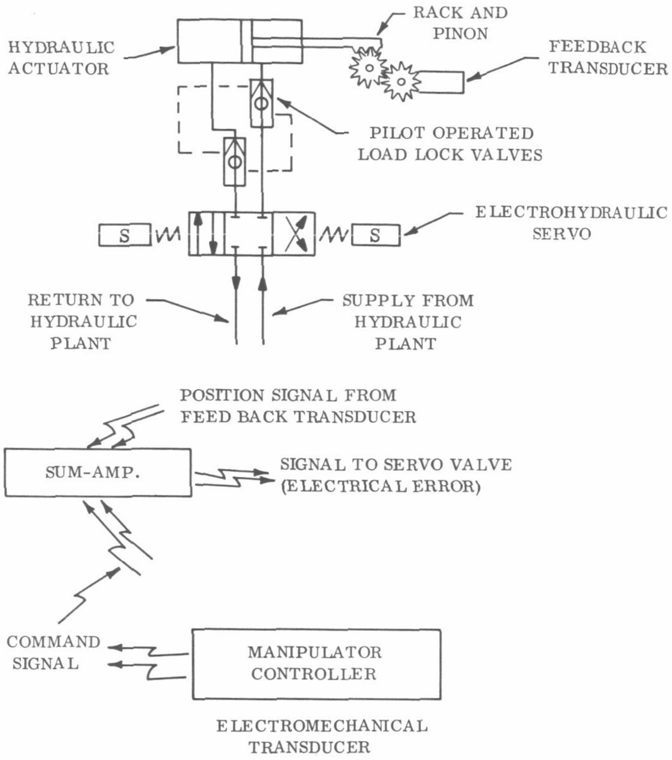


FIGURE 47.—Block diagram of a typical electrohydraulic control system for an undersea manipulator. (Courtesy of Electric Boat Division, General Dynamics Corp.)

In some small submersibles—where this type of control is especially desirable because of cramped quarters—the hull penetrations are exclusively electrical, but the teleoperator actuators may be either electrical or hydraulic. To operate the manipulator, the terminus of the scale model is grasped like a pencil and moved as desired according to the scene viewed through the view port. The external manipulator follows the motions of its replica. Control promises to be easier than with an equivalent switchbox.* Ease of operation, however, is offset to some degree by the greater complexity (and lowered reliability) of the control circuitry. Additional hull penetrations are also needed for the wires carrying angle pickoff data and command signals.

As man tries to perform more complex tasks underwater, so-

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*There are no objective comparative studies as yet.

phisticated controls must supersede simpler switchboxes. The many-jointed electrohydraulic manipulator designed by Marvin Minsky, at M.I.T., under sponsorship of the Office of Naval Research, illustrates the potentialities of model control and the trend away from anthropomorphic configurations in undersea work (fig. 48).

It is tempting to apply the "master-slave" label to the position servo control scheme described above. The "slave" portion does try to duplicate the *configuration* of the "master." Convention usually reserves the term for those closed-loop teleoperators that have the properties specified in table 3. Indeed, to many, the term "master-slave" refers only to the electrical and mechanical manipulators pioneered by Ray Goertz and his associates at Argonne National Laboratory.

In the same class as position servo control are many prostheses that employ feedback to achieve a desired result. To illustrate, consider the quandary of a man with an artificial hand who is grasping an object that is about to slip. With no sense of feel, he

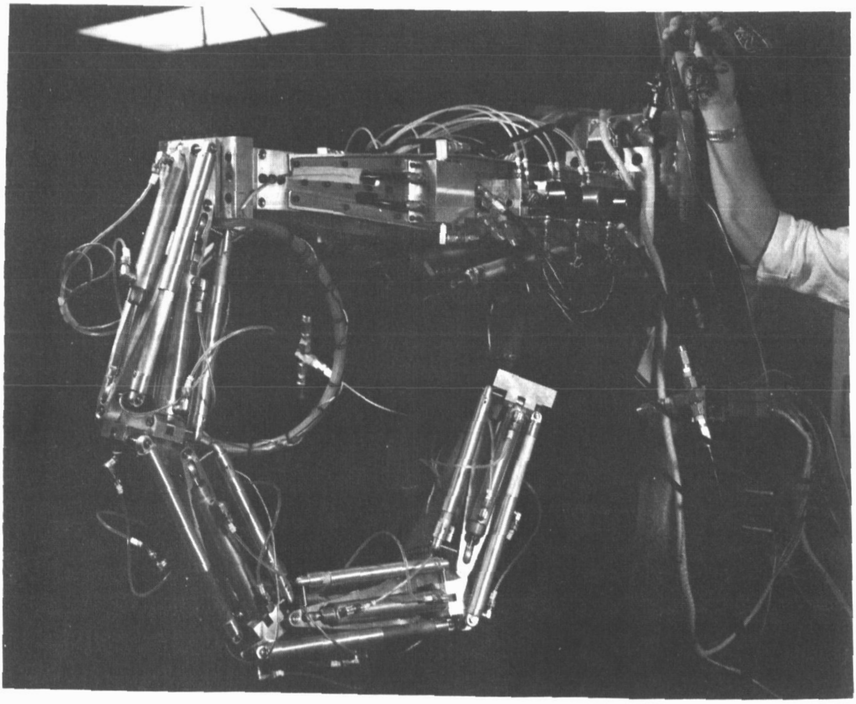

FIGURE 48.—Minsky's electrohydraulic, many-jointed manipulator arm. (Courtesy of W. M. Bennett, M.I.T.)

can only detect slippage visually and possibly too late. Dr. Fred Leonard, at the Walter Reed Army Medical Center, has overcome this problem by installing piezoelectric sensors in artificial fingers (fig. 49). The sensors pick up noise generated as two surfaces begin to slip over one another. The noise signals are converted into a command that causes the artificial hand to increase its grip until the slippage noise ceases. In this instance, the control circuitry (a local loop) operates to eliminate the noise feedback that is the error signal.

Moving on to closed-loop teleoperators with force feedback, we come first to those man-machine systems linked together by mechanical control cables, tapes, leather thongs, puppet strings, etc. Artificial-limb harnesses have been under development for centuries and are found in complex profusion (refs. 50 and 51). The fundamental concept can be illustrated by the simple use of arm flexion to close an artificial hand ("terminal device" in the language of prosthetics). A below-the-elbow amputee may close his artificial hand by moving his arm and/or shoulder on the amputated side. The motion pulls the control cable, causing it to close

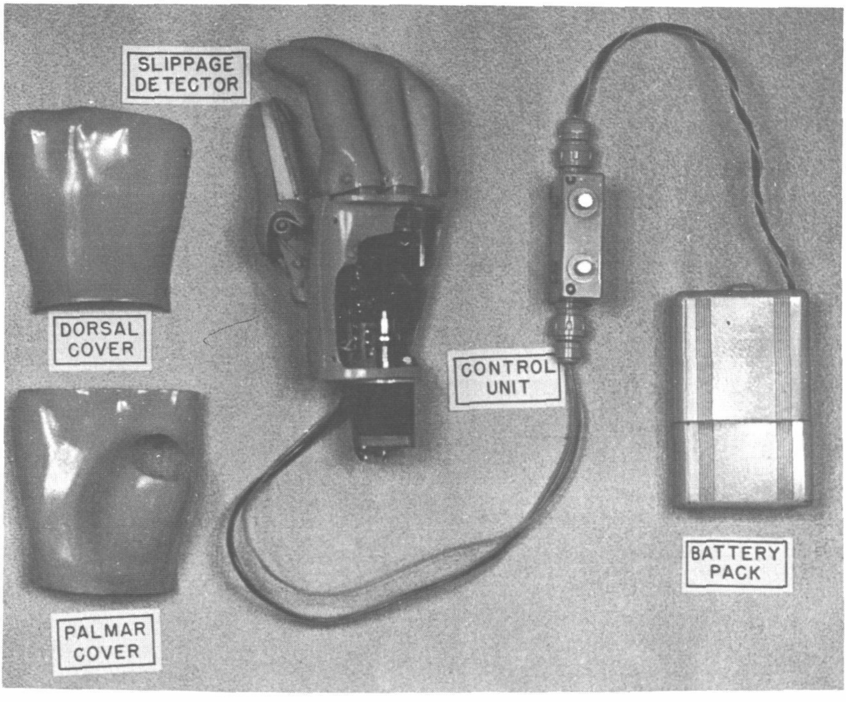

FIGURE 49.—Leonard's artificial hand with automatic grip control. (Courtesy of F. Leonard, Walter Reed Army Medical Center.)

the spring-loaded hand. The user can detect the amount of force applied by the hand and provide all of the power and control signals. The control loop is closed through the eye and force feedback.

It is a short step from the prosthetic harness to the mechanical master-slave manipulator, in which cables directly transmit the motions and forces applied by the operator (fig. 50). A mechanical master-slave is bilateral; the master end can be operated from the slave end (if one cares to venture into a hot cell to try it out). Power is provided by the human operator; but, if friction and loads are not kept low, operation can be very tiring. However, mechanical master-slaves with very low friction and resistance to movement may also be undesirable because the operator tends to lose his "feel" of the machine. The situation is analogous to power steering in an automobile; some measure of resistance in the steering wheel is desirable. The control loop in mechanical master-slaves is closed through this sense of feel, as well as through the operator's eyes.

Mechanical master-slaves are built in rough anthropomorphic

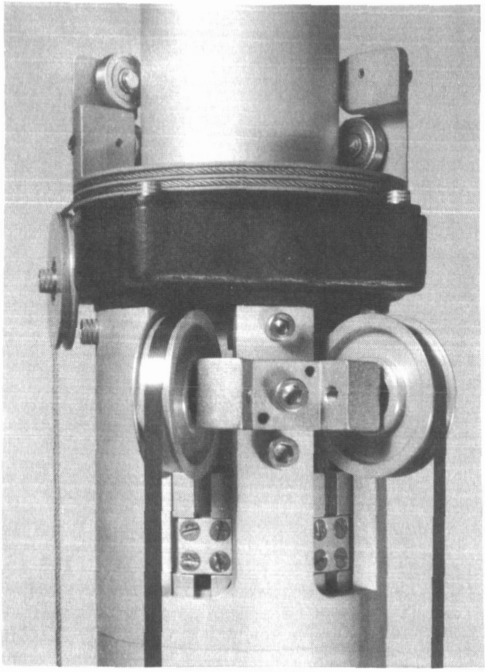

FIGURE 50.—CRL Model-8 Z-motion steel tapes. Control cables for rotation are also shown. (Courtesy of Central Research Laboratories.)

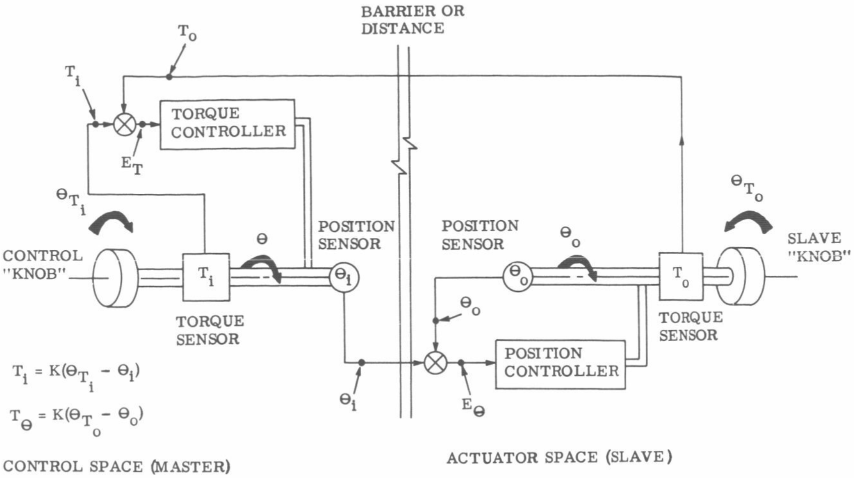

FIGURE 51.—Schematic diagram for a force-reflecting servo. See text for description of operation and definition of symbols. A somewhat different version of this schematic was used in actual manipulator construction at ANL.

form. On the master side, the operator inserts his fingers into holes more reminiscent of a mitten than a glove. Viewing the slave arms and hands through a window, the operator mentally identifies his hand with a terminal device of the manipulator; his forearms are vaguely analogous to the manipulator arms. The situation can be made even more anthropomorphic by fitting the operator with exoskeletal controls and putting joints in the slave arms like those possessed by the operator. This has been done for one electrohydraulic manipulator (Handyman), but only on an experimental basis for purely mechanical master-slaves.

Mechanical linkages between master and slave are often undesirable (in deep submersibles) and sometimes impossible (deep-space teleoperators). To overcome this objection, Ray Goertz and his group at Argonne National Laboratory developed the electrical master-slave manipulator. This was a milestone in the history of teleoperators. So we will describe the control subsystem of one of the Argonne electrical manipulators in some detail.

The schematic in fig. 51 illustrates the general concept behind bilateral, closed-loop, force-reflecting, electric manipulators. Assume that the operator applies a torque to the input control knob.* A signal, T_1, from the master-side torque sensor (say, a strain

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*This discussion follows that of Goertz and Bevilacqua (ref. 52).

gage) will be transmitted to the torque controller, which, in turn, will signal a servo motor and attached position sensor to rotate in the direction of the applied torque. The electrical signal representing angular change on the master side, θ_1, is sent across the barrier to the position controller that then commands a slave-side servo to turn the slave knob. Under no-load conditions, the position controller will null out the error signal arising from the difference in shaft positions very easily, and output will follow input with very little input torque required. If, however, resistance is encountered, the slave-side torque sensor will send back a signal, T_0, to the torque controller which opposes T_1, causing the master shaft to slow down and stop unless the input torque is increased to exceed the resisting torque. The operator can feel the resistance reflected from the slave side through the counter torque in the control shaft. Like the mechanical master-slave, this system is bilateral and can be actuated from the slave end. By proper adjustments of gains, the slave manipulator can be made considerably stronger than the operator through "force multiplication," something possible but more difficult with cable and tape linkages.

The Argonne Mark E4A is one of the latest in a series of electrical master-slaves dating from the early 1950's (ref. 53). (In this section, only the control aspects of the Mark E4A will be covered. See chapter 5 for mechanical details of the actuators.) The operator's input motions and forces are communicated to drums and position sensors via metal tape linkages (fig. 52). On the slave side, the situation is reversed where servo motors drive metal tapes that actuate the slave arm and hand. Each of the seven degrees of freedom requires a master servo drive unit with two, 60-cycle, low inertia Diehl servo motors (fig. 53). On the slave side, four servos are used. Geared synchromotors on each side provide positional information. The servo system block diagram is presented in fig. 54. Manifestly, the Mark E4A is considerably more complex than, say, a primitive ball-in-socket hot-cell manipulator; but it offers more versatility, sense of feel, and, of course, can operate across physical barriers and distance via hardwire and radio signals. Future teleoperators employed in space exploration will almost certainly rely on the Mark E4A technology.

In applications where the slave manipulator must be much more powerful than the operator, the electric servo motors of the Mark E4A can be replaced by analogous hydraulic actuators. A typical electrohydraulic master-slave is the General Electric Handyman, built for the Aircraft Nuclear Propulsion (ANP)

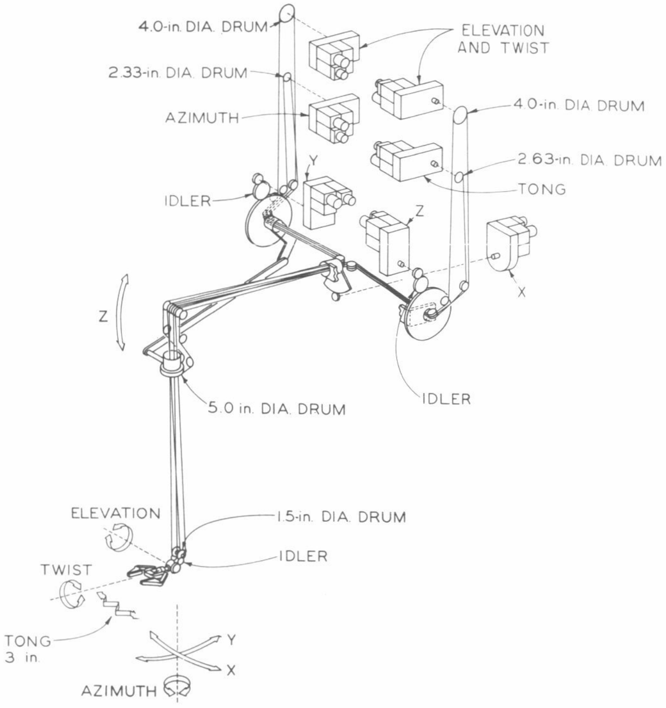

FIGURE 52.—The ANL Mark E4A slave-arm schematic drawing. The drawing for the master arm is similar (ref. 53).

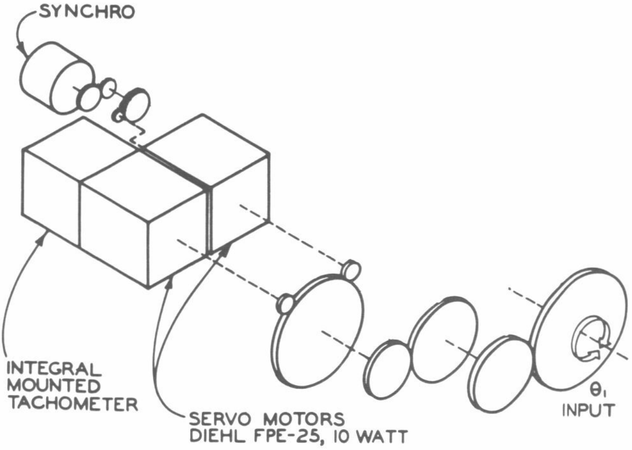

FIGURE 53.—ANL E4A master-servo drive unit. The slave-servo units are similar (ref. 53).

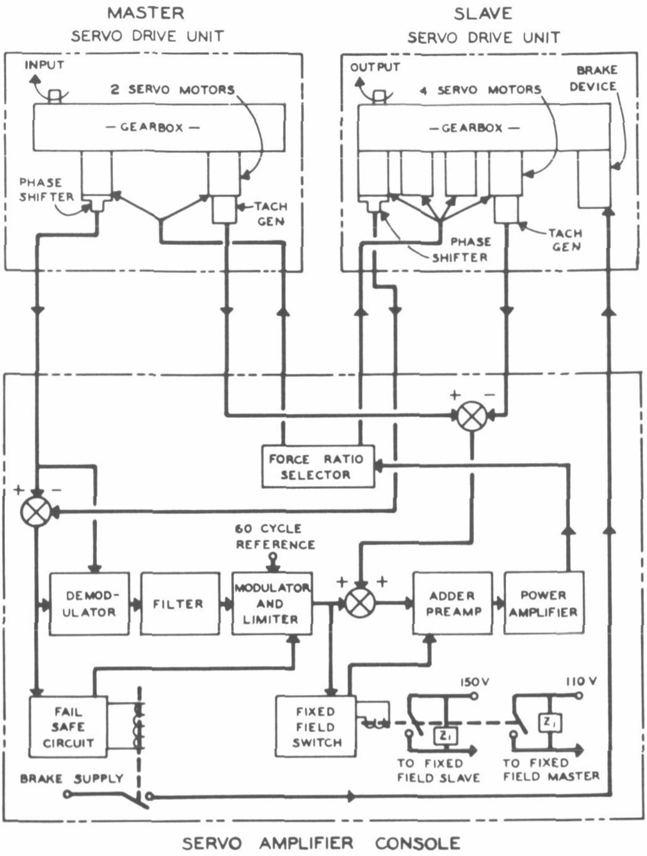

FIGURE 54.—ANL E4A servo-system block diagram (ref. 53).

program (ref. 54). The basic servo block diagram is shown in fig. 55. The similarity to fig. 52 is very strong, except that switches and servo motors are now replaced by servo valves and actuators. Motion of the master arm creates a position error signal that causes the slave ram to drive the slave arm. If the slave arm encounters resistance, the position error increases and the circuits open the master servo valve to generate a reflected force proportional to the amount of desynchronization. The actual Handyman control circuits are more complex than the simplified block; there are twenty control loops, one for each degree of freedom.

Electropneumatic teleoperators have also been constructed, viz., the Central Research Laboratories hand, pictured in fig. 56. Another manipulator of interest is the all-hydraulic Hydroman built by Oak Ridge National Laboratory for hot-cell work (fig. 57) (ref. 55).

Teleoperator control obviously has many fascinating facets. Perhaps the most impressive feature is the complexity of the wires, cables, hydraulic lines, and other conveyors of signals and forces needed to project just a few of man's many degrees of freedom through barriers or across space.

THE COMMUNICATIONS SUBSYSTEM

The teleoperator communications subsystem carries information among all subsystems. The heaviest traffic is from the sensors to the control subsystem and from the control subsystem to the actuator subsystem. There often are, however, numerous communication channels that "short-circuit" the control subsystem completely, such as those that aid in automatic temperature stabilization and those that improve grip control in advanced artificial hands. These local "loops" are analogous to the systems of human nerve fibers that transmit the reflex signals that bypass the brain. Local signals are carried from point to point within the teleoperator by "hardwire;" that is, ordinary electrical wires and cables. Hardwire communication is, in fact, the only type of data link employed to any significant extent in today's teleoperators in addition to the inescapable mechanical tapes, cables, and gears.

What kinds of communication links are physically possible? We consider here only the channels between the control subsystem and

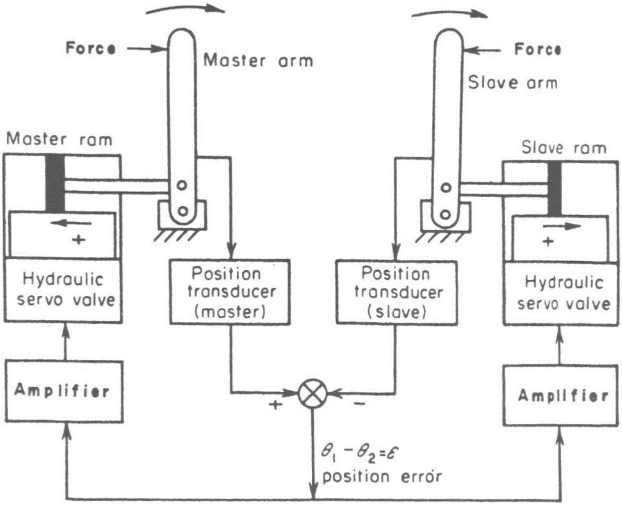

FIGURE 55.—Bilateral position servo block diagram for the Handyman electrohydraulic master-slave manipulator built by General Electric (adapted from ref. 54).

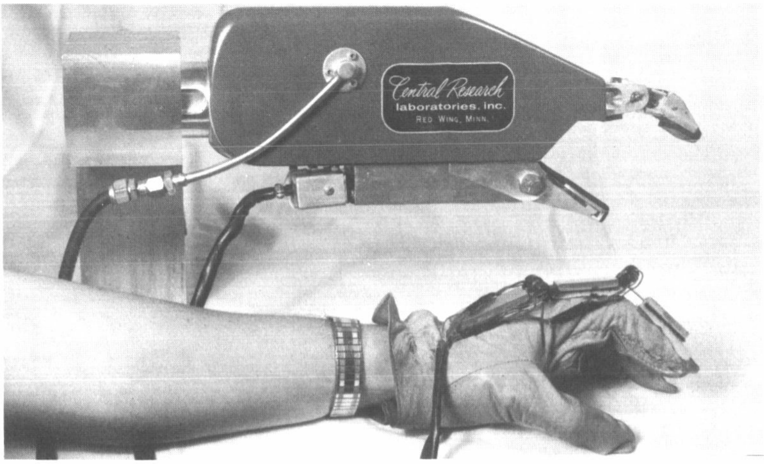

FIGURE 56.—The CRL electropneumatic hand. (Courtesy of Central Research Laboratories, Inc.)

the other subsystems, not only because they dominate the communication picture, but also because it is here that the greatest variety of links exists. This fecundity doubtless results from the frequent separation of the human operator by large distances and/or physical barriers.

If the human operator is physically close to the actuator, mechanical and hydraulic communication links are simple and reliable. When separation distances exceed a dozen feet or so, electrical cables (hardwire) supplant mechanical and hydraulic links. Cables are technically feasible up to distances of perhaps a few miles, particularly in undersea applications where radio communication is difficult or unfeasible. Beyond the practical range of cables, the intervening medium must carry the signals. In outer space, there is little choice except trains of electromagnetic waves; i.e., radio or light signals. Beneath the sea, acoustic communication links are possible, although relatively undeveloped. The choice of the communication system thus depends upon distance and the regime of application. Current solutions are summarized in table 5. (One important communication link not mentioned in the preceding discussion is provided by reflected light waves "modulated" by the scene in the operating space. Since direct viewing is intimately connected with the subject of sensor subsystems, its full discussion has been deferred to chapter 6.)

The basic commodity of communication is information. We want to transmit it without distortion, without the addition of noise, and as cheaply as possibly (ref. 56). Distortion and noise cannot be completely eliminated, however, because the medium itself and the communication equipment introduce perturbations beyond the control of the designer. Information is a commodity that may be treated mathematically in a way similar to the state variables employed in thermodynamics. No matter how hard the engineer tries, perfect transmission of information, like a 100 per cent efficient heat engine, is impossible. Not surprisingly, the more nearly perfect communication is made, say, through the use of redundant and error-correcting codes, the more expensive each piece of information (the bit) becomes. "Expense" in a communication system is generally measured in terms of bandwidth or power required.

In teleoperator design, the problems of noise, bandwidth and power are particularly acute. On the "command" portion of the link, dozens, perhaps scores of degrees of freedom must be controlled smoothly and with precision. This implies a very wide bandwidth. A whole experiment may be jeopardized if noise or a "bit error" is somehow introduced into the link. On the return or data portion of the link, environmental sensor information is

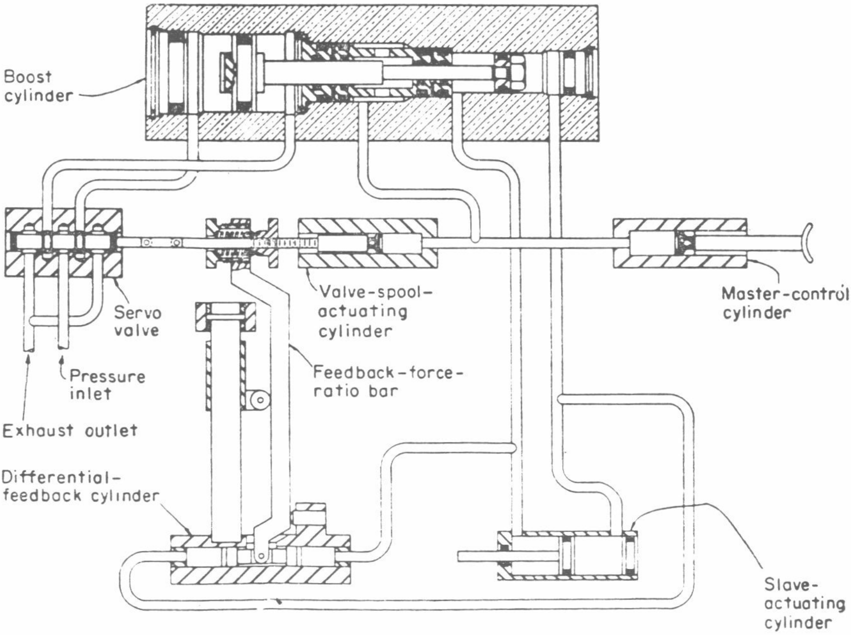

FIGURE 57.—Hydraulic control circuit for the Oak Ridge Hydroman heavy-duty manipulator (adapted from ref. 55).

likely to be video (TV), which also demands a wide bandwidth. The so-called "status" information that tells the operator the positions, velocities, and applied forces for each degree of freedom and the "health" of the teleoperator needs considerable bandwidth. Transmitter power can solve bandwidth and noise problems in a brute-force sort of way, but hostile environments generally make power a scarce commodity.

Teleoperator commands and the returning sensor signals may be analog or digital. The teleoperator's present state of development makes inter-subsystem communication primarily analog. In analog transmissions, the magnitude of the signal is proportional to the quantity being measured or the magnitude of the change commanded of a particular degree of freedom. Ordinary mechanical master-slaves and unilateral manipulators both use analog communication. If developments in space technology indicate trends, analog communication will eventually give way to digital communication, especially where distances are great and where digital computers are added to supplement man or to compress information.* There is a great advantage in having all commands and data expressed in the same format and language.

When operator and actuators are physically close, each degree of freedom can be handled economically with a separate communication channel, viz., a metal cable, hardwire, or hydraulic link. As distance increases, multiwire cables are replaced by single strand cables and finally by electromagnetic or perhaps acoustic waves. When this happens, the commands for each degree of freedom and data from all sensors (in short, all information) often share the same communication channel. Sharing is accomplished by time or frequency multiplexing. In time multiplexing, synchronous electrical or mechanical switches sample each sensor periodically. In frequency multiplexing, data from different sensors are impressed upon subcarriers at different frequencies. In space work, time multiplexing is more common.

The act of impressing information upon a communication channel is termed "modulation," and varieties of modulation exist in bewildering confusion. Amplitude and frequency modulation have been employed for decades in industry and scientific telemetry. In space technology, however, pulse modulation seems to be gaining the upper hand, pulse-code modulation (PCM) in particular (fig.

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*Note that teleoperator actuator commands are commonly three-valued; i.e., (1) rotate right, (2) rotate left, (3) do nothing. This fact could lead to trinary rather than the binary coding now common in computers and space communication.

58). Although PCM requires more power and bandwidth than the well-proven and reliable PAM (pulse amplitude modulation), PCM is better matched to the digital computers widely used to interpret, compress, and process large quantities of data. Although space program experience may not dictate future developments in teleoperators, it seems likely that sophisticated teleoperators will draw on this huge reservoir of experience.

Turning back to the basic types of links, we find that two types —the electromagnetic (radio, light) and the acoustic—"broadcast" or "beam" their signals through space or water. In either case, the signals are attenuated by the inverse square law and absorption in the medium. These laws are well known (refs. 56 and 57). The hardwire, mechanical, hydraulic, and pneumatic links all depend upon a physical "conduit" to convey signals back and forth. The conduit of course absorbs a portion of the signal, but the attenuation of the inverse-square law is circumvented. Noise is usually lower on these links, although there may be cross talk between adjacent hardwire conductors.

One of the critical spots in any physical signal conduit is the spot where it pierces the barrier between the operator and the hostile environment. In hot cells, for example, radioactive dust may leak around and through mechanical manipulators. In a deep-diving submersible, every hull penetration is a weak spot in an environment where pressures are great. For this reason, hull penetrations are nearly always electrical (which are smaller and allow no fluid passage) rather than hydraulic. The basic constraints limiting the use of physical links are cost and the inconvenience

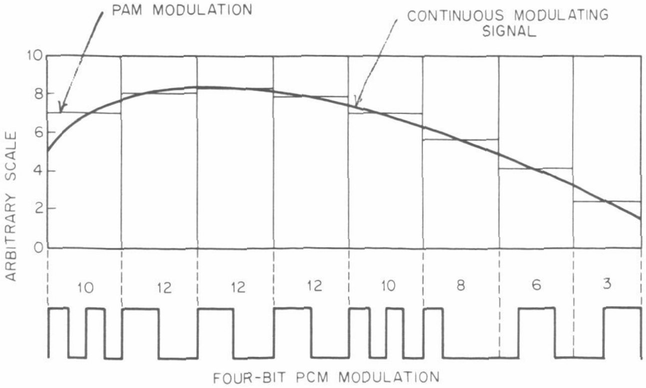

FIGURE 58.—Comparison of PAM and PCM modulation. The PCM pulses are based on a four-bit word. The decimal equivalent is indicated above the word.

of maintaining or dragging vulnerable cables hooked to mobile and distant fixed teleoperators.

Table 7 summarizes the characteristics of the basic communication links associated with teleoperator communication.

TABLE 7.—*Characteristics of Teleoperator Communication Links.*

Type of link	Characteristics	Examples
Mechanical	Analog and continuous. One cable or tape per degree of freedom or sensor. Power may be transmitted at the same time as commands. Limited to short ranges (tens of feet). Hard to make good barrier seals.	Mechanical master-slaves. Tongs, ball-in-socket manipulators. Micro-manipulators in electronics and biology. Prostheses.
Hardwire (electrical)	Analog and/or digital. Continuous or multiplexed. Cables may be many-stranded or multiplexed. Power may be transmitted at the same time as commands. Limited to a few miles in length, except when adaptable to terrestrial communication nets already in existence; i.e., commercial and government hardwire networks. Cables are inconvenient and often vulnerable to the hostile environment.	Electrical master-slaves. All fixed and some mobile unilateral manipulators. Submersible hull penetrations. Undersea stations (Benthic Lab). Some prostheses.
Hydraulic	Same as mechanical links. Leakage is a problem.	Heavy-duty unilateral manipulators (forging types) and exoskeletons (Handyman).
Pneumatic	Same as mechanical links. Leakage is a problem.	Some prostheses (Heidelberg arm) and special purpose manipulators.
Electro-magnetic	Analog or digital. Continuous or multiplexed. Length of link unlimited. Inverse-square-law and medium attenuation. Extraneous noise is a problem.	Radio-controlled mobile manipulators (MRMU). Potentially applicable in all space operations. Lasers.
Acoustic	Same as radio links. Bandwidths more restricted than radio.	Potentially applicable in all underwater operations. Disney Audio Animatronics System.

THE COMPUTER SUBSYSTEM

When teleoperators are engaged in space and undersea exploration, a general purpose computer will be desirable for such functions as:

1. Data compression and processing,
2. Lengthy computations (i.e., coordinate transformations),
3. Preview and supervisory control (see earlier discussion in this chapter),
4. Data memory in cases where subroutines must be stored,
5. The generation of artificial displays for the operator in situations where visual displays are impossible,
6. Forecasting the outcome of specific operator actions (similar to preview control, only looking into the future rather than guessing the present).

The presence of a general purpose computer in a teleoperator system may not markedly diminish the need for many small, local, analog and digital computers associated with sundry subsystem functions. Most sophisticated teleoperators, for example, will have one or more theromstatically controlled regions, some voltage and power regulators, attitude-stabilization devices, and so on. These local control loops, with their small analog computers and/or logic circuits will have little of the flexibility and power of the general purpose computer. They are, however, ubiquitous in most complex machines.

The teleoperator computer is more likely to be digital than analog. Analog computers are very useful in specialized applications, such as autopilots, but do not have the memory capacity and versatility needed for advanced teleoperator concepts. The digital computer fits very nicely into the teleoperator that employs pulse-code-modulated (PCM) communication for commands and sensor data. PCM is the natural "language" of computers and most advanced remote-control systems.

The physical location of the computer depends upon the application. In actuality, there may be two (or even more) computers in a complex teleoperator. On a distant planet a teleoperator will probably require a local general-purpose computer for supervisory control and data compression prior to transmission. The operator on the Earth will want another computer for preview control because of the long time delays involved and for display generation.

The same possibilities occur in undersea exploration save for the time-delay problem. Bandwidths in undersea communications systems are likely to be restricted (especially if an acoustic link is used) and an on-the-spot computer can improve overall performance greatly by compressing sensor data prior to transmission back to the operator.

Many small general purpose digital computers have been constructed for the manned space flight program. Teleoperator computer technology can build directly upon this base.

THE PROPULSION SUBSYSTEM

Mobility is essential to the success of many teleoperators. Man's incomparable dexterity would be next to useless if he could not walk about and apply it. A teleoperator might employ any form of locomotion that has been invented, however, the pertinent column in table 5 indicates that each application area has concentrated upon only a few types of propulsion. As a generalization, it can be said that teleoperator propulsion tends strongly to be unspecialized because the keynote of the teleoperator is versatility. On land, for example, tracked vehicles are usually preferred to wheels which demand a smooth, unlittered, hard pavement. In a similar vein, buoyant submersibles are usually superior to ocean-bottom crawlers because they can move more freely.

In orbital or interplanetary space, the so-called "reaction engine" is the only practical prime mover. The engines required are of course rocket engines, but small ones suffice in this case because only small thrusts are needed for orbital adjustment and rendezvous. Of the two basic types of "chemical" engines—solid and liquid—only the liquid engines have the multiple restart capability and throttleability essential for precision maneuvering.* Even with the choice narrowed this far, there are many propellant combinations to choose from: bipropellants, monopropellants, cold pressurized gas, etc. This selection problem was faced during the Independent Manned Manipulator (IMM) study carried out by Ling-Temco-Vought (LTV) and ANL for the Marshall Space Flight Center in 1966 (ref. 58). Its approach and conclusions are most useful here.

Two vehicles were examined during this study: a Maneuvering Work Platform (MWP) and a "Space Taxi." Both vehicles had electrical master-slaves attached but the MWP will be used here as a reference design. The MWP guidelines and requirements are listed in table 8, and are representative of orbital space teleoperators circa 1970.

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*Electrical propulsion might prove desirable in more advanced teleoperators.

TABLE 8.—*Guidelines and Requirements for Propulsion Subsystem Design for the Maneuvering Work Platform (MWP).*

Guidelines:	In-orbit service and maintenance	
	A single-point failure will not prevent a return to the parent ship	
	Minimum exhaust-plume effects (heating, etc.)	
	Maximum use of existing hardware	
	Expendable resupply at 120-day intervals	
	Re-service of vehicle following each mission	
Requirements:	Required impulse per task	45,000 lb-sec
	Total yearly impulse	739,000 lb-sec
	Tasks per year	62
	Number of thrusters	24
	Thruster thrust	13 lbs

During the LTV propulsion study, one bipropellant (nitrogen tetroxide and Aerozine 50), two monopropellants (hydrazine, 90 percent hydrogen peroxide), and cold nitrogen gas propellant were investigated in detail. The bipropellant combination is used in the Apollo Program and is a good representative of the state of the art. It does, though, have a high combustion temperature which leads to exhaust-plume heating problems. Hydrogen peroxide also has been used extensively in space, but is not easily stored for long periods. Cold nitrogen gas under pressure is innocuous enough, but it possesses no intrinsic energy and consequently has a very low specific impulse. The best choice for the MWP was reported to be hydrazine. This conclusion was buttressed with the weighting and evaluation scheme shown in table 9. The evaluation scheme, by the way, is a common one in systems analysis, regardless of the application area.

The propulsion system for the Maneuvering Work Platform is more complex than one might expect. Figure 59 shows the usual valves and gages expected of a precision thrust system for close-up maneuvering, but a gas-pressurization system is also shown. To avoid the complexity of a pump, gas pressure is created by a hydrazine gas generator. This pressure forces propellant through the system. Finally, if the propellant is to be at the storage tank orifice when needed, a positive expulsion device must be installed when operating in a zero-g environment. A non-metallic positive expulsion bladder was selected over metal bellows and various surface-tension schemes on the basis of weight and degree of development.

For other space teleoperators other types of propulsion might

TABLE 9.—*MWP Propellant Selection Weighting Scheme.**

Parameter	Characteristics			Weighting factor	Rating		
	N_2O_4 – Aerozine 50	N_2H_4	H_2O_2		N_2O_4 – Aerozine 50	N_2H_4	H_2O_2
Resupply volume	16 ft^3	22 ft^3	26 ft^3	8	8	5.8	5
Technical risk							
Development time	12 months	10 months	8 months	8	5.3	6.4	8
Development status	Good	Good	Best				
Complexity							
Number of components	101	61	64	7	3.5	7	7
Installation problems							
Reservicing characteristics	3 fluids	2 fluids	2 fluids				
Hardware cost	\$3.8x10^6	\$2.5x10^6	\$2.3x10^6	7	4.3	6.4	7
Propulsion system volume	3.3 ft^3	4.2 ft^3	5.6 ft^3	7	7	5.5	4.6
Plume heating	T_c 5000°F	T_c 1770°F	T_c 1350°F	5	1.4	3.8	5
Propulsion system weight	268 lbs.	288 lbs.	355 lbs.	4	4	3.7	3
Plume deposition	Potential problem	None	None	4	2	4	4
Resupply weight	1110 lbs.	1450 lbs.	2000 lbs.	4	4	3.1	2.1
Propellant storability	Excellent	Excellent	Fair	4	4	4	2
Propellant logistics	Same as Apollo	Different from Appollo		3	3	1.5	1.5
				61	46.5	51.2	49.2

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*Ref. 58.

be more suitable, but the general approach used during the LTV study should be applicable to most orbital missions.

Mobility beneath the sea involves remarkably similar considerations. A small, manipulator-carrying submersible hovers when it possesses neutral buoyancy in much the way a satellite "floats" in space. As a submersible approaches its target, it must maneuver and dock, just like its space counterpart. The "engines" in this environment are nearly always propellers or water jets that can be controlled in thrust level, thrust direction, or both. During actual manipulation tasks, the submersible will generally be anchored to the target and attitude changes can be made with the docking arms or "grapplers;" propulsion is needed only during approach and docking.

The small submersibles require speed of only a few knots. The *Autec I* vehicle can cruise at 2 knots for 8 hours, and has a maximum submerged speed of 3 knots (ref. 59). It is designed to hover ± 5 feet at depths below 200 feet. The Deep Submergence Rescue Vehicle (*DSRV*) is a couple of knots faster and must be able to hover over a given spot against a 1 knot current, at attitudes up to 45° from the horizontal. Most submersibles meet such requirements through the use of screws of various types, such as

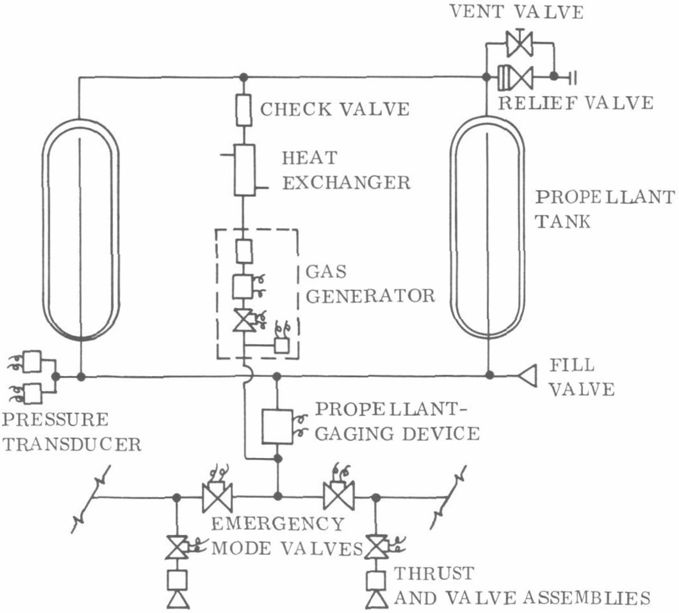

FIGURE 59.—MWP propulsion subsystem schematic diagram proposed in the LTV-ANL-MSFC study (adapted from ref. 58).

those illustrated in fig. 60. Usually a single main screw provides propulsion until target rendezvous begins. Then auxiliary screws or jets mounted in pairs around the vehicle provide precise control for hovering, up-and-down motion, and any other maneuvers needed.

Tracked vehicles may have important applications on those portions of the continental shelves where bottom conditions are suitable. The Scripps Remote Underwater Manipulator (RUM) is a major example of bottom crawlers (fig. 17). RUM was propelled through two independently driven electric motors (ref. 60). Each track was powered by a 7½ horsepower, 800 rpm, dc motor. Power was provided from shore in all RUM tests through a 5-mile-long multiconductor cable.

The nuclear industry—first to use manipulators on a wide scale—was also the first to place them on vehicles. Most AEC laboratories have developed their own or purchased commercially made mobile manipulators for emergency use. The PaR-1 vehicle (fig. 23) is representative of the smaller tracked vehicles in this class. Mobot and MRMU illustrate the medium and large classes respectively (although they are both inoperative at present). Most manipulator-bearing vehicles used in AEC facilities are driven by electric motors and depend upon long power cables. MRMU, which is radio-controlled, is an exception; it is powered by a gasoline engine and can attain a speed of 35 mph. MRMU's chassis is a converted, full-tracked Army XM474 cargo carrier.

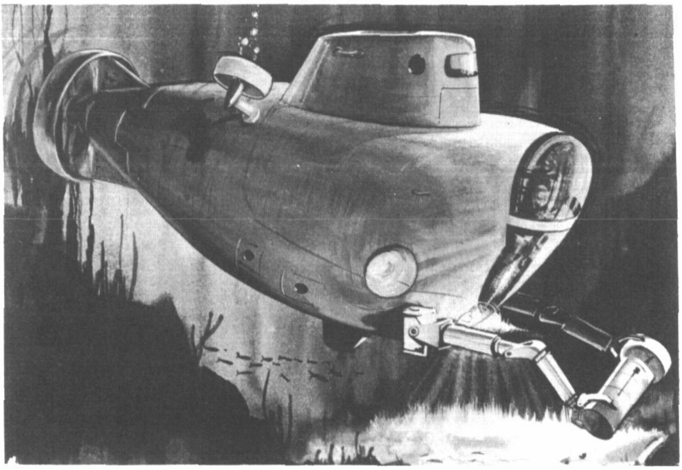

FIGURE 60.—Artist's concept of the *AUTEC I* and *Alvin II* submersibles, showing the main propulsion system aft and attitude-control propellers on the sides. (Courtesy of Electric Boat Division, General Dynamics Corp.).

The many manipulator-carrying vehicles now in use in different nuclear installations are described in reference 61.

In many nuclear operations, the working areas are usually quite cluttered (especially during emergencies and rescue operations) and therefore unsuitable for wheeled vehicles on the floor. Manipulators mounted on wheels riding on overhead crane-type tracks see considerable service in such situations. The large wall-mounted manipulators installed in the E-MAD building at the AEC-NASA Nuclear Rocket Development Station in Nevada operate on this principle (fig. 22). Driven by electric motors that pick power off metal strips along the E-MAD walls, these manipulators can range up and down the length of an immense hot cell.

The only major type of vehicle not mentioned so far in this section is the large, heavy-duty forging manipulator that transports hot forgings and billets in foundries. Teleoperators employed in mining and construction work would be similar in size and power, but would undoubtedly substitute tracks for wheels.

THE POWER SUBSYSTEM

When motion is communicated between the operator and the actuators by mechanical means—cables, metal tapes, etc.—the power source is usually man himself, as in most prosthetic devices. The human is a good power source when the target is close by, not too heavy, and the tasks are not too tedious.

If commercial power lines are nearby, the power problem is minimized. In many hostile and distant environments, however, neither man's power nor commercial electricity can be conveniently communicated to the actuators. Teleoperators then can either carry power sources along with them or try to extract energy from the environment, as suggested schematically in fig. 61.

Except for a few space concepts employing solar cells and teleoperators used near commercial electrical power, transportable power sources are dominant. Chemical sources, such as internal combustion engines, trail far behind human power in current hardware. Batteries and compressed gas bottles provide limited amounts of power, especially in prosthetics. Nuclear power plants seem promising for future deep space and undersea activities. Table 5 gives specifics by application area.

Manipulation requires that raw power—heat, electricity, sunlight, and so on—be converted into mechanical energy. As subsystems are defined here, the task of converting raw power to mechanical energy falls to the transducers in the actuator subsystem; that is, to the electrical and/or hydraulic motors, pistons, etc. (These transducers will be covered in detail in the next chapter.) The actuator subsystem usually consumes power in a form different from the raw power produced by the power subsystem. The same is true with the other subsystems, except that they are more likely to require electricity than hydraulic power. Electricity, after all, is the life's blood of modern man-machine systems. In most cases, therefore, the teleoperator power subsystem will need a rather elaborate power conversion section that converts the basic power generated by the source into power for each subsystem at the correct voltage, pressure, and degree of regulation needed. Current thinking separates power *conversion* from power *conditioning,* as indicated in fig. 61.

Power conversion is a large field, and, except for a few general remarks, we shall rely on references to key data sources and the specific examples of teleoperator power supplies that follow (ref. 62).

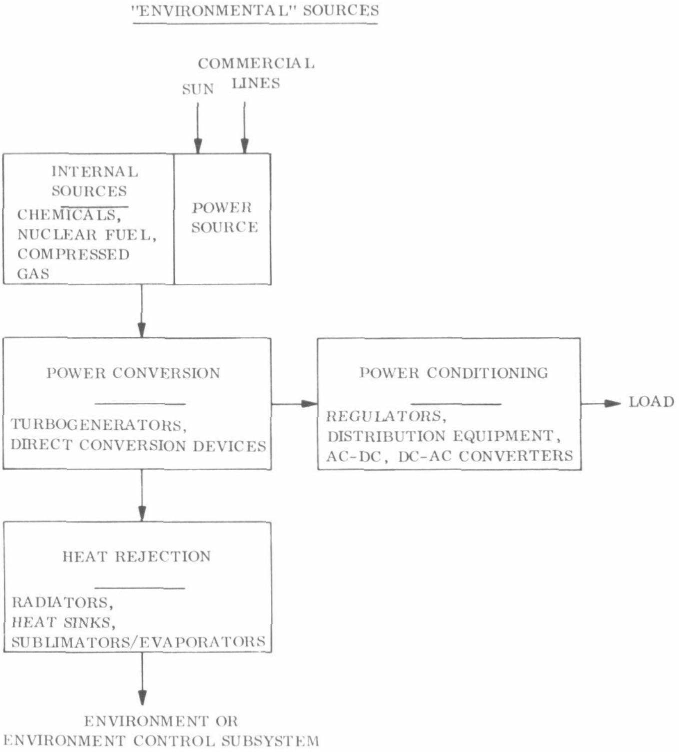

FIGURE 61.—Generalized block diagram of the teleoperator power subsystem.

With heat engines, efficiency may be only 5 to 35 percent; with fuel cells and batteries, it may approach 90 percent. The problem here is not only that hard-to-get energy is inevitably thrown away, but that, in many instances, it is *very difficult* to throw away waste energy. The final block in fig. 61 shows how the energy rejection step fits into the overall power picture.

There is a slow unmistakable trend in power subsystem design toward direct conversion devices, such as fuel cells and thermoelectric elements. It is tempting to say that the removal of moving parts can only improve reliability, but teleoperators are not ordinary machines. Teleoperators, for example, *must* have many moving parts if they are to succeed. Reliability may actually be improved by generating mechanical motion in the power subsystem directly and then conveying it more or less directly to the actuators, treads, wheels, and other moving parts. An automobile's hydraulic power take-off is a good example. To summarize this rather elusive point: teleoperators always have moving parts, and static power conversion may be less reliable than dynamic power conversion, i.e., turbogenerators, etc.

It is impractical to survey all power sources used on or proposed for teleoperators. Some entries in table 10 are well-developed, e.g., gasoline engines (a type of "chemical" engine). A few others are far enough along in development to be used as examples.

One is accustomed to thinking in terms of solar cells for the power source on long, unmanned trips to the planets; but, for short, manned missions in orbital space, chemical power sources are usually superior on a weight/cost basis.

The Maneuvering Work Platform (MWP) examined by LTV and ANL (ref. 58) assumed a one-year operational life, with approximately 62 eight-hour missions during that period. Since the safety of the astronaut-operator was paramount, no single-point failure modes were permitted. An excellent view of typical teleoperator power requirements in orbital flight can be found in tables 11 and 12 (from ref. 58). In making the power estimates, the specific teleoperator task was assumed to be the erection of a space telescope. On this mission the average electrical power required was about 250 watts.

For forays of a few hours duration from a parent satellite, the only power sources that proved reasonable on the bases of weight and volume for the MWP were chemical power-plants that could be recharged upon return to the parent ship. Batteries, fuel cells, and chemical turbogenerators all met the basic requirements. Chemical turbogenerators, however, required large quantities of

TABLE 10.—*Teleoperator Power Requirements and Power Plant Perspective.*

Application area	Teleoperator (only) power range (kw)[1]	Commercial electric lines	Solar	Human power	Chemical sources	Nuclear sources[4]	Compressed gas sources
Aerospace:							
orbital vehicles	0.1–5		P	P	P*	P	
planetary probes	0.5–2		P			P	
space chambers	0.1–0.5	P		U			
Undersea:							
submersibles	0.5–100				U	U[3]	
crawlers	5–500	U			P	P	
laboratories	0.1–1	P			P	P	
Nuclear:							
master-slaves	0.1–0.5	U		U			
vehicles	1–500	U			U		
unilateral	0.1–1	U					
Terrestrial transportation:							
walking machines	10–500				P		
man-amplifiers	50–250				P*		
Medical:							
prosthetics	0.1–0.5			U[2]	U*	P	U*
surgery	?	P					

Chemical: master-slaves	0.1–0.5			U			
Metal processing: forging manipulators	10–500	U			U		
Electronics: master-slaves	0.1–0.5	P		U			
Construction: vehicles	10–500				P		
Public service: vehicles	10–500				P		
Entertainment: "puppets"	0.01–1	U					

Key to symbols:
P = proposed.
U = in use now or in past.
* = discussed in text.

[1] Average requirements; peak demands may be much higher; includes lighting, communications, etc.

[2] Human motions (breathing, etc.) may be transformed into electrical energy and stored for later use.

[3] Classified information.

[4] Nuclear reactor or radioisotope heat sources.

reactants and produced severe heat loads on the MWP environment-control subsystem. Fuel cells with the life expectancy and cyclic capability required for the MWP missions presented too many development problems; therefore, fuel cells were not con-

TABLE 11.—*MWP Electrical and Electronic Equipment Power Requirements.*

Equipment	Average power required
1. Communicaions	13.0 watts
2. Radar	50.0
3. Displays	8.0
4. Control electronics	4.0
5. Stability and control electronics	36.0
6. Environment-control subsystem	68.0
7. Thrusters	30
8. Grapplers (docking and anchoring)	124
9. Floodlight	80.0
10. Hand tool (250 w; 10% dutycycle)	25.0

TABLE 12.—*MWP Electrical Energy Requirements Analysis.*

Mission phase	Equipment operating during mission phase [1]	Energy requirement (watt-hours)
Orbital transfer	Items (1) (2) (3) (4) (5) & (6)	107.4 ± 11.2
Docking and unstowage of cargo	Items (1) (3) (4) (5) (6) (8) & (9)	285.8 ± 30.7
EVA erection of telescope	Items (1) (6) (9) & (10)	720.9 ± 85.6
Orbital transfer and maintenance trip	Items (1) (2) (3) (4) (5) (6) & (9)	204.7 ± 13.6
Maintenance (mission worksite)	Items (1) (6) & (9)	238.8 ± 31.5
Intermittent operation during mission	Items (7) & (8)	202.6 ± 33.4
	Total	1760.2 ± 266.0

[1] See entries on table 11 for number key.

sidered for the 1970 time period. The only safe choice left was the electric battery. Of the several possibilities, the silver-cadmium cell was considered most likely to meet the operational life and deep-discharge requirements.

Significantly, an examination of power requirements for a larger, farther-in-the-future (1975) Space Taxi led LTV to the choice of fuel cells. It was presumed that the fuel-cell development problems would be solved by 1975.

The power-plant considerations for small submersibles run almost parallel to those for orbital vehicles. In both application areas, relatively short expeditions from a mother ship are common. Under the sea, though, the power requirements are larger, usually because the entire vehicle is larger and the power subsystem must drive the propulsion system. Except for the nuclear power plant on the *DSRV–1*, small submersibles will use batteries for the present and the near future, with the fuel cells becoming more interesting in the 1970's. (In underwater oil well operations shore electrical power may be available at the working site.)

On dry land, electrical power sources are the most popular choice of teleoperators, except, of course, for human-powered master-slaves and artificial limbs. Nuclear and solar power are not significant today in terrestrial teleoperators. Where commercial electric lines are not available or impracticable, the only extant power sources are those that utilize chemical reactions and, in some prostheses, the energy of compressed gas.

One of the more intriguing terrestrial applications of teleoperator principles is the man-amplifier. The best-publicized conceptual engineering efforts along this line are the Cornell Aeronautical Laboratory man-amplifier studies sponsored by the Department of Defense, and the more recent "Hardiman" concept under investigation sponsored jointly by the U.S. Army and U.S. Navy. In all man-amplifiers, the human operator wears an exoskeleton with which he can perform superhuman tasks, such as lifting ton-size weights.

Superhuman performance manifestly demands superhuman power subsystems. A strong man can develop a horsepower or two for a few seconds. To be worthwhile a man-amplifier should have tens of horsepower over spans of several hours. To be transportable the power supply is likely to draw on chemical energy.

The Cornell studies (ref. 63) in the early 1960's gave us the first estimates of power requirements for a man-amplifier (table 13). About 10 horsepower was estimated for the Cornell concept. More recent Hardiman power estimates are higher: 15 horsepower-plus just for standing still and about three times that for

TABLE 13.—*Summary of Joint Servo Design Estimated Power Requirements.**

Joint	Torque (lb-ft)	Angular rate at indicated Torque (rad/sec)	Horsepower [1]	Estimated maximum angular rate at no load (rad/sec)
Elbow	2000	0.	......	22.3
	1400	0.75	1.91	
Shoulder	1650	0	......	10.5[2]
	1600	0.47	1.37	
Hip	2600	0.78	3.69	6.1[2]
Knee	1300	2.62	6.20	11.5
Ankle	950	0.20	0.35	2.6[2]

*These figures are now considered too low.

[1] This column cannot be added to get total power because all loads will not occur simultaneously.

[2] Estimated for running subject.

walking. Evidently first-generation man-amplifiers will consume as much power as a small automobile.

To power their man-amplifier, the Cornell Aeronautical Laboratory proposed two systems:

1. A hot-gas-powered electrohydraulic system (fig. 62), and
2. A hot-gas power system in which the actuators would be powered by the hot gas directly.

Neither of these power supplies was investigated in detail, either on paper or in the laboratory, but each would undoubtedly be rather bulky. Both the hot radiator in the hot-gas-hydraulic system and the hot motor exhaust in the direct-power system would be hazardous. As we shall see from the next example, present concepts for man-amplifier power supplies are large and undeveloped in comparison with power sources employed in the prosthetic field.

Most contemporary artificial limbs and orthotic devices are moved by human muscles. When this is impossible or awkward, a small power source generating a few watts may prove a blessing to a handicapped person. Unfortunately, little research has gone into what the medical people call "external power supplies" (ref. 64). The only power sources that have been investigated in any depth are compressed carbon-dioxide cylinders and electric batteries. Hydrogen peroxide is occasionally mentioned in the medical literature, but it has not been explored in terms of hardware.

The space program contributes directly to the prosthetics field through its efforts to develop long-life, rechargeable, sealed batteries of minimum weight (ref. 62). The best battery for prosthetics use today is probably the nickel-cadmium cell, a power source used on many unmanned satellites. The lighter-weight, silver-zinc cell is coming into operational use in space and will probably be found powering artificial limbs before long.

Although batteries can be recharged conveniently and compare well with compressed-gas power sources, the latter have gained

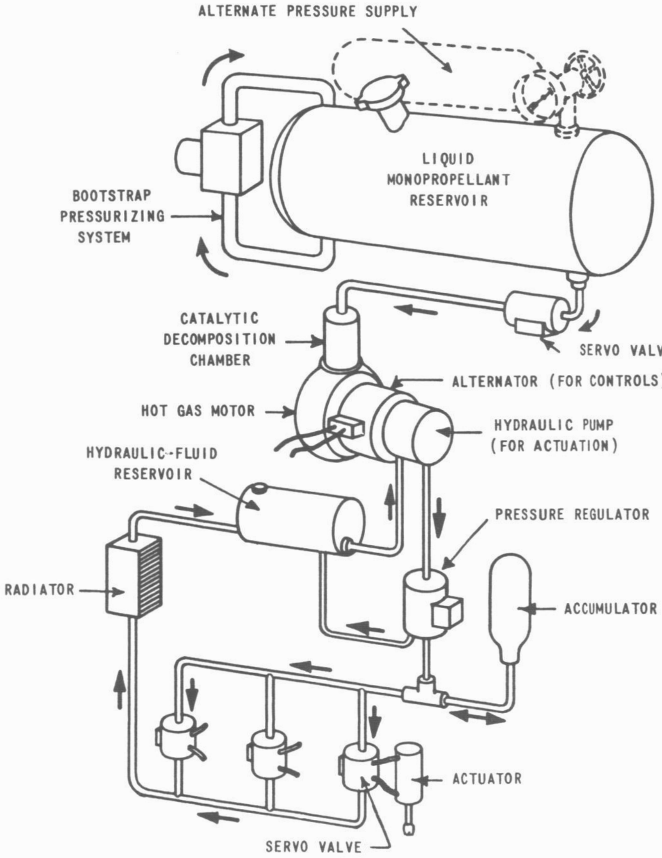

FIGURE 62.—Hot-gas-powered electrohydraulic power plant proposed by Cornell Aeronautical Laboratory for a man amplifier. (Courtesy of Cornell Aeronautical Laboratory.)

ascendancy in the prosthetics field. Mainly, this is because CO_2 capsules came into use before lightweight, reliable, sealed batteries were available and CO_2 actuators are simpler and lighter than their electrical counterparts. In addition, electric prostheses have not been notably successful. One problem is the whine of high-speed electric motors. Electrically powered artificial limbs are easy to control, however, and are more easily integrated with electromyographic and other electrical control schemes.

Compressed CO_2 is energetic enough to power artificial arms and hands for satisfactory periods of time (ref. 65). Standardized steel capsules can be refilled with liquid CO_2 by the prosthesis wearer himself. The capsules are small enough to be concealed under the clothing in many instances. In current practice, CO_2 pressure is reduced by a regulating valve to 100 psi or less and conveyed directly to the servo valve controlling the artificial limb. CO_2 cylinders are common because they have proven simple, reliable, safe, and convenient to use.

Although teleoperator power subsystems now in existence rely heavily upon chemical sources of energy and electric power lines, nuclear and solar power subsystems will certainly be developed for future space and undersea exploration. Changeovers from chemical to nuclear power will come first on those missions where power is needed over long periods of time and where resupply with chemical fuel is impossible or too costly.

THE ATTITUDE-CONTROL SUBSYSTEM

The presence of an attitude-control subsystem on a teleoperator presumes that some portion of the teleoperator is free to rotate with respect to the target or some set of reference axes. On terra firma, teleoperators generally do not need attitude-control devices because they are either fixed (master-slaves attached to a hot-cell wall) or vehicles with essentially fixed attitudes (MRMU). An attitude-control subsystem has no place on such teleoperators, unless they happen to employ a walking mechanism for translation. Some walking machines, particularly the two-legged type, do change the attitude of the operator during the walking cycle. In these cases, attitude control becomes a matter of balance and the elimination of attitude control is likely to disorient the operator. This is more in the province of actuator design, since, in the end, it is the actuators (legs) that balance the machine and stabilize the motion of the cockpit and operator. (Chapter 5 discusses these matters in more detail.)

Attitude control becomes critical on "hovering" submersibles and spacecraft which must attain and maintain certain attitudes with respect to sunken submarines, space telescopes, or other targets.

There are three important ways to control the attitude of a vehicle that is free to rotate in one or more degrees of freedom: (1) reaction engines (jets or screws), (2) gyros, and 3) docking arms or manipulator arms that can exchange angular momentum with the target or some other object.

The LTV–ANL–MSFC Independent Manned Manipulator study again gives us a reference point (ref. 58). Considering the maneuvering and docking required during the erection of an orbital telescope, the study produced angular acceleration requirements of 8 to 30 degrees/sec^2 on the pitch, roll, and yaw axes. Given the size and mass of the Maneuvering Work Platform (MWP), these requirements were translated into moment and angular-momentum requirements. To meet these requirements an all-jet reaction system was compared with a hybrid jet-gyro system. On the basis of weight and volume (including allowances for extra electrical power drain), the former was selected for the MWP.

Under the ocean, attitude-control requirements are qualitatively similar to those in space, but quantitatively different because of the larger vehicle sizes, turbulence, ocean currents, and the viscosity of seawater. Attitude control is aided in deepsea work by (1) the ready availability of propellant (water); (2) the presence of a strong gravity field that permits attitude trimming by shifting the center of mass relative to the center of buoyancy (say, through the use of pumped mercury), and (3) the use of anchors.

Small submersibles may use translation propulsion systems for attitude control. The main propulsion system, however, may not prove suitable in maneuvers necessitating frequent propeller reversals. For this reason, special nozzles and/or ducted propellers (called "cross-hull thrusters") usually are located around the hulls of manipulator-carrying submersibles (fig. 60, ref. 59).

The attitude of a submersible or spacecraft is so easily perturbed that operating philosophy recommends stabilizing the vehicle with respect to the target with grappling arms that mechanically or magnetically "grab" the target structure and position the vehicle relative to it. Precision attitude control, then, is a function needed only when the vehicle is approaching and leaving the target or mother ship.

THE ENVIRONMENT-CONTROL SUBSYSTEM

Environment control, like attitude control, becomes critical in teleoperator design when outer space, the undersea, or radiation fields, are invaded. Teleoperators in strong nuclear radiation fields have to be shielded from the deleterious effects. A more difficult problem—temperature control—is important in outer space where there is no atmosphere or ocean to keep the power-consuming and (consequently) heat-producing teleoperator cool.

The two problems are not completely independent. On unmanned missions, such as the Benthic Laboratory or a Martian probe, no life support equipment may be needed, but the artificial atmosphere that could serve as a heat sink for a variety of electronic gear will also be missing. In such cases, adequate heat conduction and/or convection paths must be provided to an external surface where the heat can be removed by radiation to space or conduction to seawater (ref. 66). Of course, the existence of a life-support system does not eliminate the problem of thermal control, it just transfers it to one of cooling the artificial atmosphere. The artificial atmosphere may not be sufficient or convenient for cooling, say, the auxiliary power unit, and special coolant loops will have to be provided.

On short, manned space missions, the environment-control subsystem must: (1) provide oxygen, (2) remove carbon dioxide, and (3) remove heat. For a relatively short mission, with resupply of expendables from a parent ship, the design of the environment-control subsystem is simplified in the following ways:

1. Bottled oxygen can be used instead of regenerative equipment.
2. Atmospheric contaminants do not have time to become concentrated, and only CO_2 needs to be removed.
3. Heat rejection can take place through a sublimator/evaporator rather than a radiator, which expends no materials but is heavier and occupies more volume.

Undersea manipulator-carrying vehicles have similar missions in terms of time and environment-control requirements. The major difference is the replacement of the external vacuum environment by cold seawater. Many of the principles used in designing space environment-control subsystems also apply to submersibles. There is now an immense body of literature dealing with life support in various hostile environments (refs. 67 and 68).

THE STRUCTURE SUBSYSTEM

The teleoperator structure performs one or both of two functions: (1) encapsulation and protection of the operators, and (2) service as a framework to support attached teleoperator components.

When protecting the operator, the structure subsystem becomes essentially a pressure shell. At great depths in the ocean, this shell may be a major design problem. Both in space and under the ocean, operator capsules tend toward spherical and ellipsoidal shapes.

A mere platform suffices for the human operator in a terrestrial walking machine. In mechanical master-slave manipulators, all structural support is provided by a simple horizontal tube penetrating the barrier separating the operator from the hostile environment; the master and slave ends of the teleoperator hang from this tube. Vehicles such as MRMU are not markedly different structurally from an ordinary truck, bulldozer, or tank. In short, few generalizations can be made about teleoperator structures. Each one is built to meet the needs at hand.

CHAPTER 5

The Actuator Subsystem

When a signal for motion is received via a teleoperator's communication subsystem, the actuator subsystem responds by applying forces or torques to the appropriate joints in its array of hands, arms, legs, and other devices. Three classes of force and torque generators are common in teleoperators:

Mechanical linkages: cables, tapes, filaments, gears, drive shafts, ball screws.
Hydraulic and pneumatic devices: pistons, motors, servos, McKibben muscles.
Electrical devices: solenoids, motors, servos, stepping motors.

Magnetic and electrostatic forces are also available to the designer but they are relatively weak and are employed rarely (ref. 69).

There are two parts to a teleoperator actuator; these are the force/torque generator and the "switch" that receives the command from the operator and applies power to the force/torque generator. The actuating signal may be mechanical, hydraulic, or electrical, depending largely upon the specific application. In principle, actuators can be electrohydraulic, all-electrical, all-hydraulic, all-mechanical, or almost any combination of signal type and force/torque generator. Some actuators, of course, are more suited to some tasks than others. Table 14 shows the six combinations emphasized in teleoperator design.

A manipulator is bilateral if force and motion can be transmitted both ways to some degree, that is, from operator controls to actuators and vice versa. If one moves the slave arm of a bilateral master-slave, the master arm should also move. By this definition, most all-mechanical master-slaves should be bilateral because input and output are rigidly connected. When tapes, cables, and shafts transmit the forces, even in simple tongs, the operator can usually "feel" what is going on at the "slave" end; he can usually move the master end by applying enough force to the "slave" end. If there is a great deal of friction, or a significant mechanical advantage between "master" and "slave," the manipulator will be *less* bilateral. With some geared systems, bilateral-

TABLE 14.—*Common Types of Teleoperator Actuators.*

Type of signal	Force/torque generators		
	Mechanical	Hydraulic	Electrical
Mechanical	Tongs* Prostheses Mechanical master-slaves	Pneumatic prostheses	Electrical prostheses
Hydraulic		Hydraulic master-slaves Forging manipulators	
Electrical		Undersea unilateral manipulators Walking machines Prostheses Exoskeletons	Electrical master-slaves Unilateral manipulators Prostheses

*In all-mechanical actuators, the operator usually transmits signals and power at the same time.

ness in effect disappears. In fact, the incorporation of ratchet mechanisms can make an all-mechanical teleoperator truly unilateral. The same observations apply to *some* all-hydraulic and *some* all-electrical teleoperators. In the Argonne National Laboratory servoed electrical master-slaves, a force on the slave arm generates a signal that results in a force at the master arm. This two-way commerce cannot occur, though, when switch-operated motors drive manipulator joints, because a simple motor cannot generate a signal at the slave end, relay it to the master end, and create a force there. Therefore, an electrical, motor-driven manipulator is usually unilateral. However, force feedback and bilateralness may be incorporated using transducers other than the primary drive motors.

The teleoperator actuator "family tree" is portrayed in fig. 63. The first branching occurs when teleoperators are classified by the type of force/torque generator used; the second florescence depends on the adjectives "unilateral" and "bilateral," while the third branching is functionally dependent (hands, feet, etc.) The sections that follow explore this "tree" and are organized in much the same way.

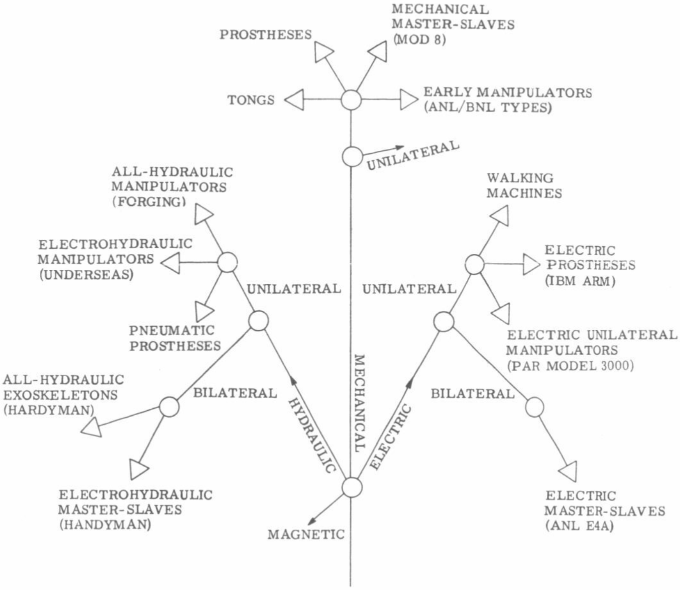

FIGURE 63.—The actuator subsystem "family tree," showing "branchings" by power source and the unilateral-bilateral attribute.

ACTUATOR DESIGN PRINCIPLES

The actuator or "effector" subsystem mimics man's arms and hands. The simple tongs used in the nuclear industry are crude caricatures of human arms, but more advanced arms under development, such as the Serpentuator and other many-jointed arms, are even more articulated than human limbs. The actuator subsystem may incorporate some motions, such as wrist extension, that biology neglected to invent. And, of course, machines can be made bigger, stronger, faster, and more precise than men.

The actuator subsystem consists of one or more arm-hand combinations. The function of the "arm" is the translation of the hand to a desired point in space and the orientation of that hand into the desired planar position. The hand should be able to duplicate some, but not necessarily all, motions of the human hand. The most obvious function of the human hand is grasping, but anyone who has watched a manipulator operator working in front of a hot-cell window knows that hitting, poking, and pushing are as much part of the performance as picking things up.

Most manipulator discussions begin with the assertion that a manipulator arm-hand combination must possess at least seven degrees of freedom to fulfill the three basic functions of:

1. Hand translation to an arbitrary point within the working volume,
2. Hand orientation to an arbitrary plane, and
3. The grasping motion.

The first two of these functions require three degrees of freedom apiece, and grasping adds a seventh. Nevertheless, many manipulators do rather well at special tasks with less than seven degrees of freedom. Ball-joint tongs, for example, can handle many jobs with only five degrees of freedom, having sacrificed two degrees of freedom by restricting hand orientation. If an obstacle lies between the teleoperator and the target, however, more than seven degrees of freedom may be needed to reach around the obstacle and properly orient the hand (fig. 64). Despite these exceptions, most of the teleoperators in service today have seven degrees of freedom and the trend is toward more degrees of freedom in space and undersea applications.

How may an arm be fashioned to meet its two basic functions of hand translation and hand orientation? The human arm is an intricate series of "links" joined end-to-end by joints that can pivot and rotate various amounts. The movable joint, then, is one of the keys to articulation. A single pivot, hinge, or sliding joint constitutes one degree of freedom (fig. 65). A joint can be given two degrees of freedom by adding rotation or a second pivot. A ball-in-socket joint can even provide three degrees of freedom—two angular and one of rotation. The manipulatory capabilities of the human arm depend entirely upon such a series of links (bones) and joints. Conceivably, all teleoperator arms could be built in this anthropomorphic fashion.

But why limit machines to nature's constructions? No need to, of course. Many manipulators have sliding or telescoping joints, such as the common wrist-extension feature. There are no design

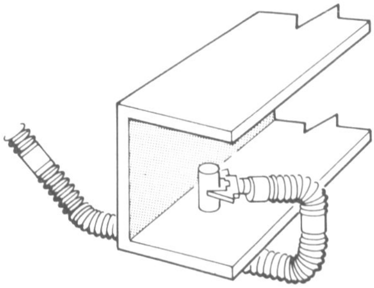

FIGURE 64.—In some applications, the teleoperator arm must possess more than the seven basic degrees of freedom.

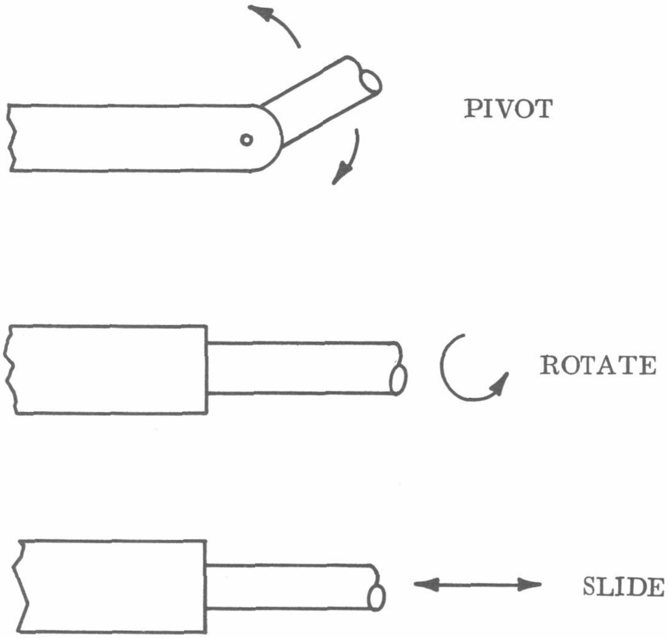

FIGURE 65.—Some typical degrees of freedom found in teleoperators. Several may be combined in a single joint.

restrictions upon the total number of joint-link combinations in a manipulator series, or in the ways in which they are connected, or even in the number of links that terminate (or originate) at a given joint. The human wrist is really a single joint with six attached links (five fingers and the forearm). A teleoperator hand or arm may employ any number of links to suit the task at hand —always limited, of course, by cost, weight, and complexity.

In spite of the abundance of diverse possibilities for arm construction (fig. 66), only a few common types have emerged.

Manipulator hands are in an even more primitive state than arms. Those introduced in the nuclear field in the 1940's had vise-type hands, in which two opposing flat surfaces are brought together on the target (fig. 67). Except for minor changes in jaw configuration and the occasional addition of special surfaces, most of the manipulators in use today have similar hands. Beakers, fuel elements, and radar knobs are all manipulated by two opposing flat surfaces. There is little "matching" between the hand and the object.

Other hand possibilities exist in profusion. The three-jaw "chuck" hand has been proposed. The versatile hook-like hand is

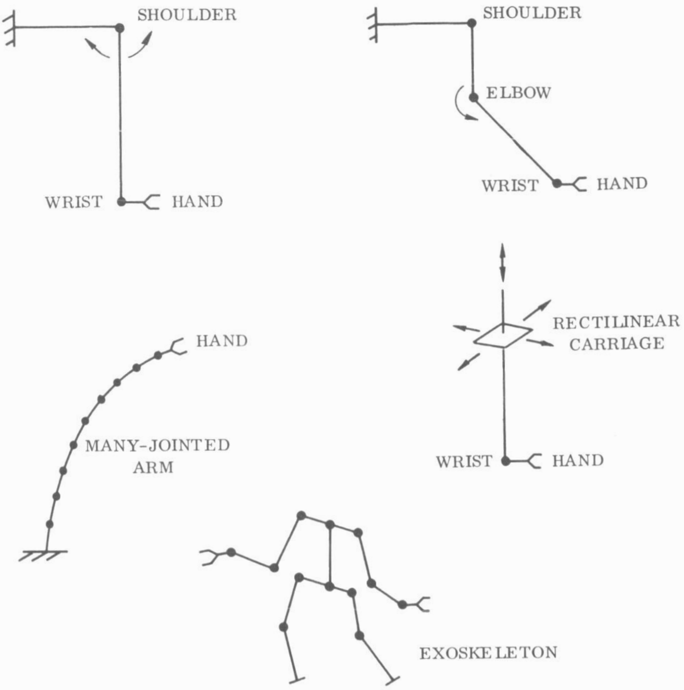

FIGURE 66.—Some possible actuator geometries. Many of these geometries are illustrated in hardware form later in this chapter.

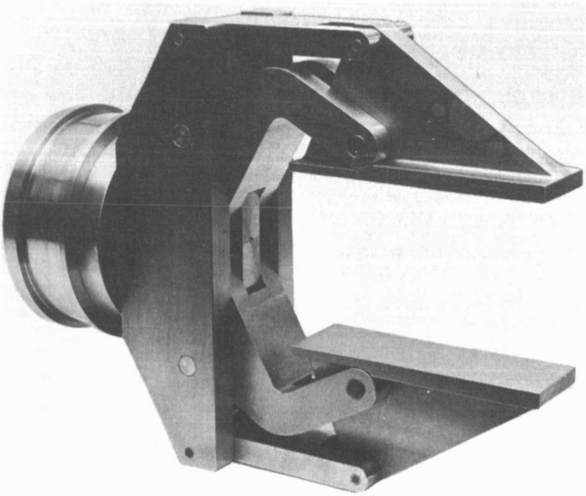

FIGURE 67.—A vise-type of manipulator hand. (Courtesy Programmed and Remote Systems Corp.)

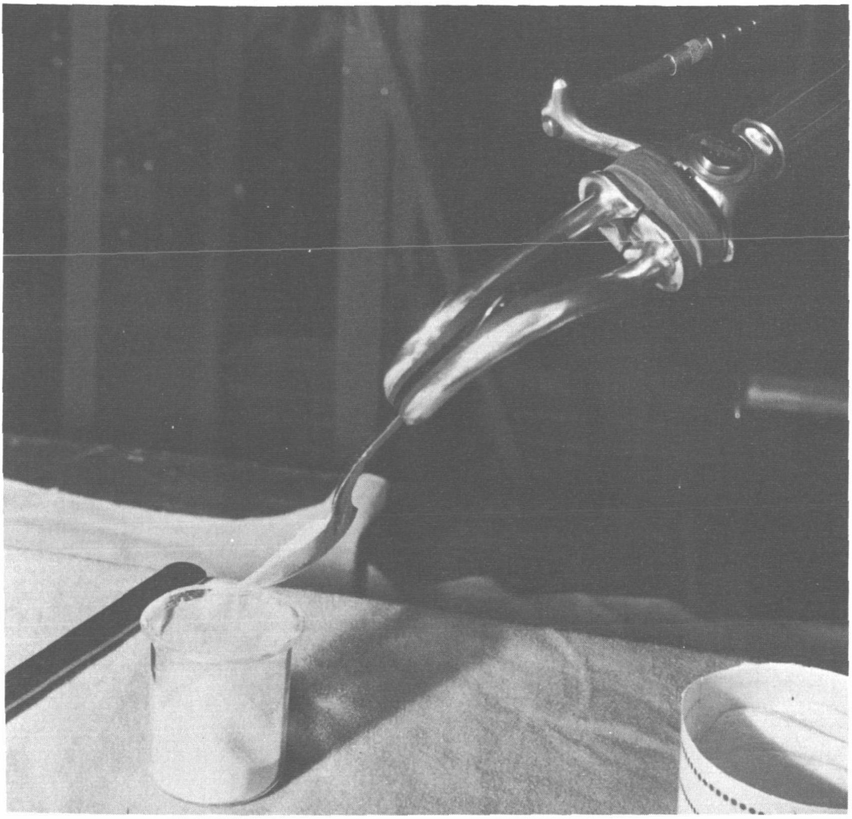

FIGURE 68.—A typical prosthetic hook. (Courtesy A. J. Hosmer Corp.).

common in prosthetics (fig. 68). But so long as the designer is restricted to one degree of freedom for the hand, little sophistication can result. After all, the human hand possesses dozens of degrees of freedom. Once articulated fingers replace the vise and chuck, the hand can begin to handle round objects with finesse and generally conform to the shape of the target.

If the teleoperator hand is defined as that part which picks things up and manipulates them, there are other (perhaps better) ways than merely squeezing (vise action) or wrapping and squeezing (hand-grasp action). Pneumatic suction forces, magnetic forces, and adhesive pads made of interlocking fibers are also possible and are more common in industry than in teleoperator design.

The most common kind of mechanical linkage between the operator controls and the actuator subsystem is the flexible metal

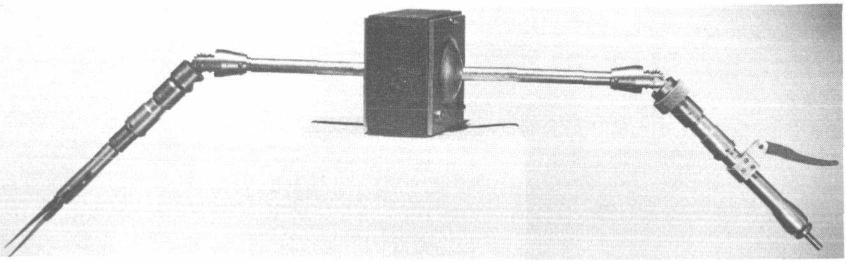

FIGURE 69.—Brookhaven articulated tongs. (Courtesy L. G. Stang, Jr., Brookhaven National Laboratory.)

tape or cable prevalent in mechanical master-slaves. With pulleys a "pull" transmitted along a tape or cable is easily transformed into linear motion or rotation of the mechanical arm. On many manipulators where loads are heavy, mechanical motion is transmitted via link chains and gears that eliminate cable and tape stretching. When a rigid rod is substituted for the flexible cable, as it is in simple tongs, rotation or torque may be conveyed directly by the same rod that transmits linear forces. Changing the direction of a force conveyed by a rigid member may be somewhat more complex than it is with a flexible cable, but various linkages employing rigid members are available, viz., the typical vise-type hand shown in fig. 67. Gears are the natural mechanisms for changing the direction of torque and rotary motion. The differential gear assembly used in one of the Brookhaven National Laboratory tongs is a good example of this approach (fig. 69). Rotation and linear motion in rigid members are easily interchanged through the use of worm gears and rack-and-pinion assemblies.

The simplest hydraulic (or pneumatic) actuator is the piston that transforms a command into linear motion or force. Any linear motion, of course, may be subsequently modified in magnitude and direction by the mechanical devices. "Simple" pistons become rather complex when provided with all the valves and connections required for positive, two-way, controlled action. Nevertheless, hydraulic actuators are gradually replacing electric actuators in undersea unilateral manipulators. Important advantages of hydraulic actuators are the ease with which force amplification can be achieved, and their innate ability to transmit high forces per unit volume of actuator. Almost all heavy-duty teleoperators, such as forging manipulators, employ hydraulic actuators.

An electrical analog exists for each of the hydraulic actuators;

the solenoid replaces the piston, and many varieties of electric motors and servos have been developed. Electrical actuators are easy to activate and control. They are compatible with electrical signal communication and the electrical power subsystems common in teleoperator work. But electrical actuators are relatively weak. Motors, for example, must operate at high speed through long, backlash-prone gear trains to generate powerful forces. Still, the attractiveness of electrical actuation has led engineers to apply it to every field, from artificial electrical arms for the handicapped to the high-capacity wall-mounted manipulators at NRDS in Nevada.

Before dealing with specific pieces of hardware, the subject of actuator subsystem figures of merit must be broached. From the many diverse qualities used by manipulator engineers in describing their equipment, one would presume that their arms and hands possess many-sided, complex personalities; and, being extensions of man, the hardware does seem to assume a personality of its own. The list of descriptors and figures of merit that follows is at once a glossary and an intercomparison of different types of actuators.

Descriptor or Figure of Merit	*Definitions, Comments, and Intercomparisons*
Volume of motion	The manipulator's working volume, assuming no obstructions, is related to arm reach and its degrees of freedom.
Torque	Usually applied to wrist action and the ability to tighten nuts and bolts, etc., but also a property of any rotating joint.
Load rating	The force or lift capability available in a teleoperator arm-hand assembly. In manipulators and prostheses, the lift or load rating is that figure attainable over thousands of lift cycles. Jelatis has pointed out that at present there is no universally accepted basis for such measurements (ref. 70). Although hydraulic arms are generally used in high load situations, in principle, any

Descriptor or Figure of Merit	*Definitions, Comments, and Intercomparisons*
	type of arm can be designed for any load. The load rating usually decreases with "reach."
Squeeze	A "hand" rating similar to the load rating described above. The same comments apply.
Speed	The linear or angular rate at which a joint or the end point (hand) of a series of joints moves. Hydraulic arms are usually rather sluggish, but speed can often be traded for force through the mechanical-advantage route. In principle, any arm can be designed to whatever speed is desired, though other factors will suffer.
Mass or weight	This factor is particularly important in space applications; it depends upon the load rating, working volume, and other factors.
Accuracy	An arm or hand is accurate if it responds to a command (say, rotate hand 30° clockwise) with some agreed-upon degree of precision. Accuracy depends upon the control subsystem to a large extent.
Ease of indexing	The ability of an arm-hand assembly to move into a prescribed configuration, viz., a compact, "stowed" position on a submersible.
Stowability	Ability to achieve a compact, flush configuration, usually within a well or compartment on a vehicle.
Articulateness	A measure of the number of joints and degrees of freedom. Note that too much articulateness may confuse the operator. Dexterity is usually synonymous

Descriptor or Figure of Merit	*Definitions, Comments, and Intercomparisons*
	with articulateness, though in actuality it depends heavily upon the quality of the control subsystem.
Stiffness	A synonym for manipulator rigidity. A stiff manipulator will tire the operator. This is an important parameter in unpowered teleoperators.
Inertia	A measure of the difficulty of accelerating and decelerating the actuator subsystem over and above inherent friction and the time lags caused by circuitry and linkages. Teleoperator inertia can cause overshooting and oscillations (hunting) about a target position. Too much inertia will tire the operator of a master-slave.
Sponginess	This is a characteristic of pneumatic teleoperators in which controls and actuators are connected by a compressible fluid.
Backlash	Geared force-transmission systems display this property, which is measured by the amount the actuator (or control) must be moved in the reverse direction before the commanded joint begins to move.
Friction	Resistance to motion over and above inertia. Friction can also tire the master-slave operator.
Stability	The ability to move smoothly from one configuration to another and maintain it without jitter or hunting. Depends largely on control subsystem design.
Sensitivity	A teleoperator is sensitive if a slight motion of the controls

Descriptor or Figure of Merit	*Definitions, Comments, and Intercomparisons*
	causes arm or hand motion. Often "play" or a "deadband" will be built into the system to prevent excessive sensitivity.
Drift	Electrical and hydraulic actuator subsystems may move very slightly in a continuous fashion on account of servo "leakage."
Cross coupling	When motion in one degree of freedom causes motion in another, cross coupling exists. This occasionally occurs in mechanically coupled systems.
Compliance	A measure of the match between the motion requirements of the task and the motion capabilities of the manipulator. Discussed at length in chapter 3.
Maintainability/ repairability	The ease of gaining access to the actuator subsystem and effecting repairs, etc.
Reliability	The capability of the subsystem to operate successfully for a specific period of time. Reliability is related to complexity. The more complex electrical and electrohydraulic bilateral master-slaves are generally less reliable than simple all-mechanical actuators.
Ruggedness	A hard-to-define term that usually means that a piece of equipment can survive rough treatment successfully. Strictly speaking, ruggedness is not related to load rating.
Fail-safe capability	When a teleoperator fails or loses power, say, in a control circuit, the actuator subsystem should maintain its configuration rather than drop objects held in the hand, etc.

Descriptor or Figure of Merit	*Definitions, Comments, and Intercomparisons*
Self-protectivity	Actuators should be designed with limit switches and other devices that prevent them from being overloaded beyond the damage point or smashing against supports, and so on.
Self-repair capability	Arm-hand pairs can be arranged so that one can repair the other without the necessity of men entering a hostile environment.
Cost	Electrical and electrohydraulic servo manipulators are considerably more expensive than mechanical master-slaves, although higher performance is claimed.
Power requirement.	All-mechanical teleoperators require no external motive power at all, while electrical master-slaves need several kilowatts. Power is critical in space and undersea work.
Support-equipment requirements	Again, the electrical and electrohydraulic teleoperators are at a disadvantage because they require banks of supporting electronic gear and trained technicians.
Operator skill required	The effective matching of the man-machine interfaces can ease the skill requirements.
Resistance to the environment	Actuators must be designed to resist the corrosion, vacuum, temperature, radiation, and other aspects of the environment in which they are immersed. The simpler, all-mechanical teleoperators usually fare best in difficult environments.
Cosmesis	In prosthetics, particularly, the actuators should look natural and be relatively noiseless.

This long list of actuator design factors illustrates the difficulty of teleoperator design, the multitude of tradeoffs, and the subtle interfaces. None of the factors listed above is independent of others, and there is no single over-riding figure of merit. These actuator-oriented parameters are all related in diverse, complicated, and often unknown ways to the system-wide figures of merit discussed in chapter 3. Since no one really knows all of the interrelations, much teleoperator engineering remains intuitive and a matter of experience.

ALL-MECHANICAL ACTUATOR SUBSYSTEMS

One of the earliest "hostile" environments that man encountered was high temperature. He quickly developed all manner of pokers and tongs for manipulating hot objects. Other "remote handlers" were constructed for working with chemicals and other hazardous materials. These are so well known that they will be bypassed here.

In the nuclear industry thought for personnel safety led first to long tongs—some, with pistol grips, such as that illustrated in fig. 70. Nuclear radiation, though, proved impossible to attenuate sufficiently by distance alone. A way had to be found to use tongs through walls of lead bricks and concrete. The obvious solutions were to go over the barrier with jointed tongs or through the barrier with the aid of a flexible joint fixed in the wall. Both approaches met with success.

Ball-joint or ball-swivel tongs are sometimes supported in a thick ball of lead or uranium, encased in steel and located in a socket in the barrier (fig. 70). The ball is free to rotate, although friction forces may be high. Some balls "float" on a blast of com-

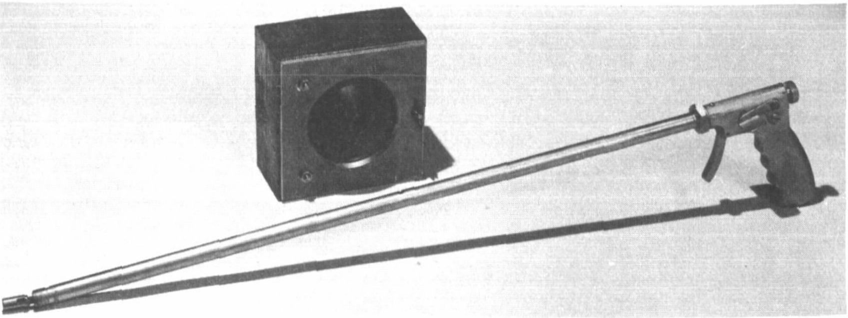

FIGURE 70.—Ball-swivel tongs with pistol-grip actuator. Tong fingers have been removed. (Courtesy of L. G. Stang, Jr., Brookhaven National Laboratory.)

pressed air from below that reduces friction significantly. Another slightly different solution is the so-called "castle manipulator" (ref. 71). Instead of a ball, it utilizes a cylinder within a cylinder to achieve two degrees of freedom. A third degree of freedom arises when the tongs are permitted to slide back and forth through the joint; a fourth is gained when the tong shaft can rotate the hand; and a fifth, when the grasping motion is added to the hand through mechanical or hydraulic linkages. Unarticulated tongs are sometimes as long as 14 feet.

The straight, unarticulated, ball-swivel tongs can reach only those targets located within the 65° cone permitted by the joint, and then only with limited orientation of the hand. Several types

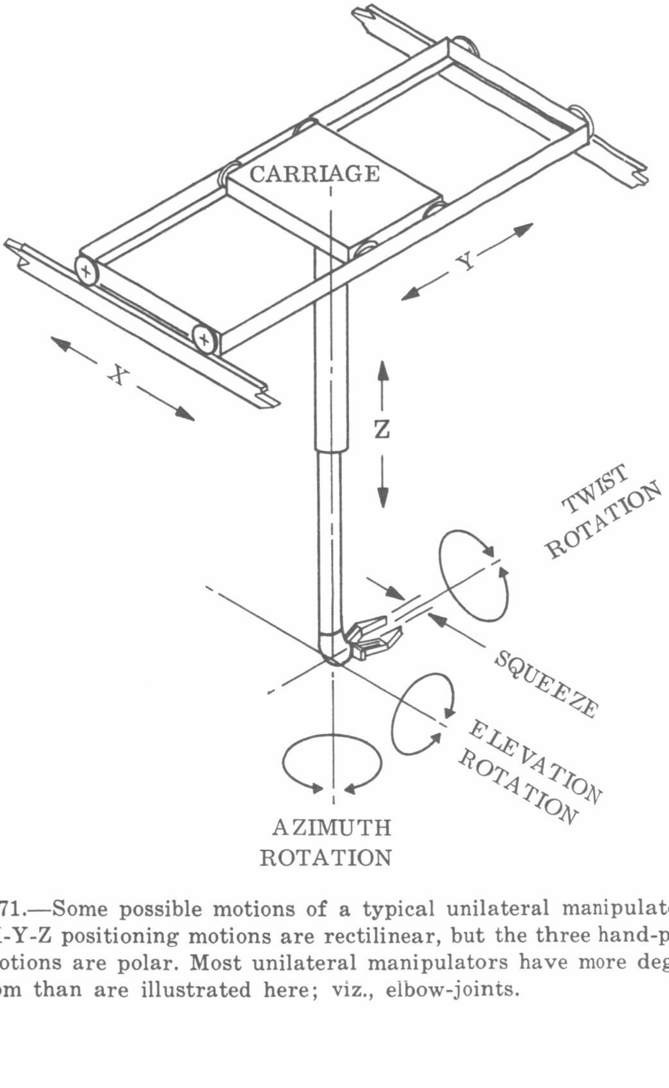

FIGURE 71.—Some possible motions of a typical unilateral manipulator arm. The X-Y-Z positioning motions are rectilinear, but the three hand-positioning motions are polar. Most unilateral manipulators have more degrees of freedom than are illustrated here; viz., elbow-joints.

of articulated tongs overcome some of these deficiencies. These tongs are usually jointed, as shown in fig. 69, and permit more flexibility in hot-cell operations (ref. 72). Models with direct spatial correspondence of motion, mirror-image correspondence, or both, are available. The driving torque for the extra joint is transmitted by means of an internal drive shaft and gearing at each joint.

The tongs just described are all "bilateral" in the sense that motion may be transmitted from either end. Interestingly enough, the mirror-image motion possible with some articulated tongs takes them out of the master-slave class, because spatial correspondence is lost, although they are still bilateral.

Through-the-wall tongs have proven very useful in the nuclear and chemical industries, but they are still restricted to relatively small operating volumes and are hampered by their lack of the full seven degrees of freedom required for dexterous tasks. Over-the-wall manipulators and additional degrees of freedom came simultaneously.

Some Unilateral Mechanical Manipulators

Goertz has described an early over-the-wall manipulator in

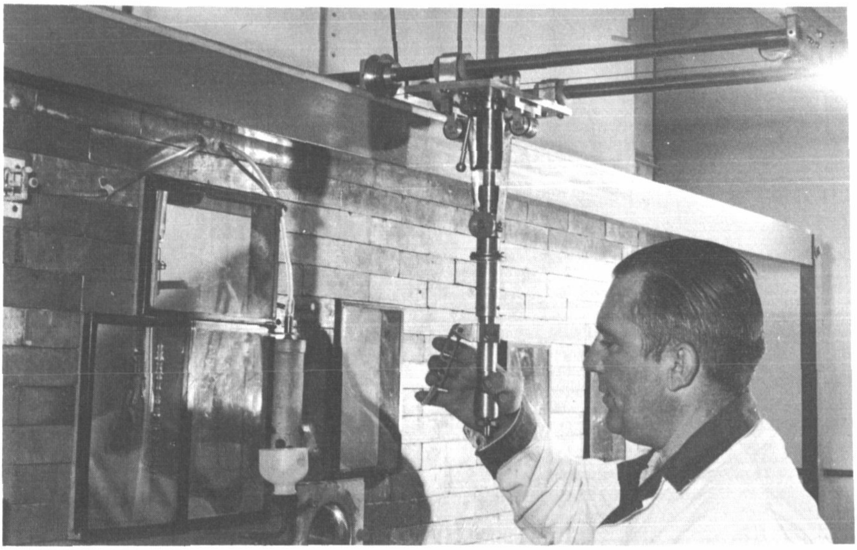

FIGURE 72.—In the Brookhaven BNL–3 mechanical manipulator, column rotation was communicated from the control station to the operating station via the cable linkage shown. The long cable system precludes effective force feedback. (Courtesy of L. G. Stang, Jr., Brookhaven National Laboratory.)

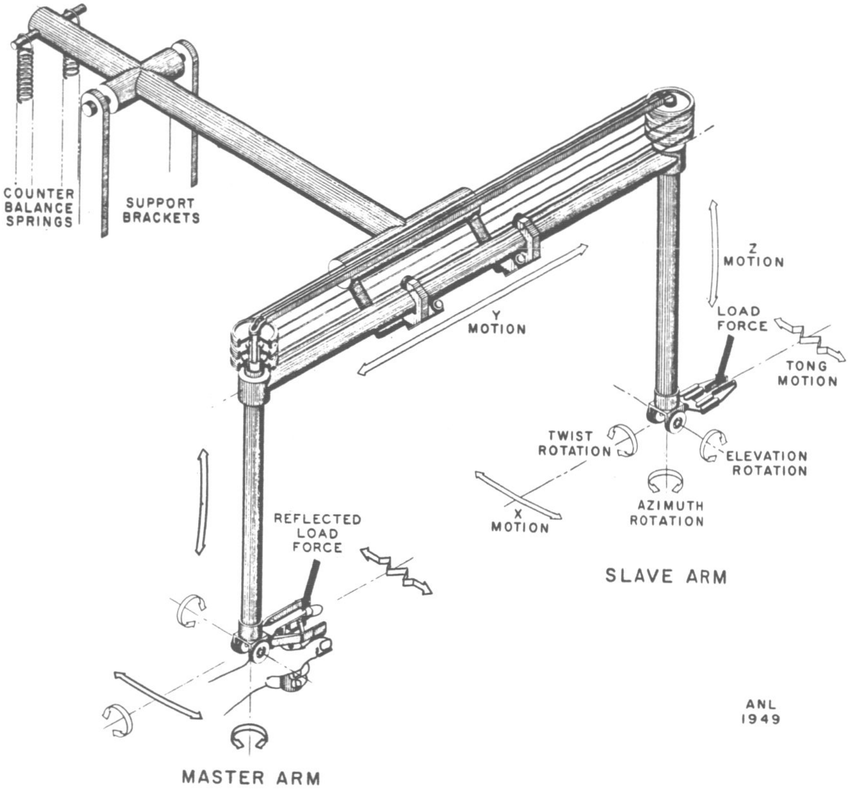

FIGURE 73.—The ANL Model–M1 mechanical master-slave, circa 1948. The horizontal support tube went over the wall of the hot cell. (Courtesy of Argonne National Laboratory.)

which most of the seven degrees of freedom were controlled by mechanical means (ref. 73). This Argonne Laboratory manipulator has been termed "unilateral" because force reflection in the various degrees of freedom is attenuated to uselessness through friction and mechanical advantages. Still, in principle, force can be transmitted in both directions. This same manipulator is also "rectilinear" in the sense that the hand is positioned in two dimensions by an overhead carriage moving in X–Y coordinates, and by a vertical column moving up and down along the Z axis (fig. 71). Hand positioning, then, was in rectangular coordinates, and the adjective "rectilinear" became attached to all manipulators relying on overhead bridges for positioning, even though other degrees of freedom were polar.

Like Argonne, Brookhaven National Laboratory has developed

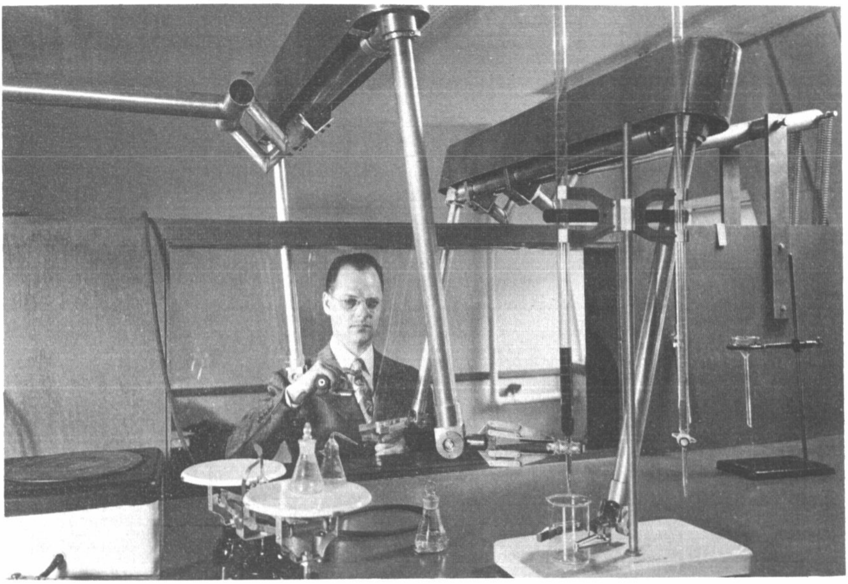

FIGURE 74.—The ANL Model–M1 mechanical master-slave, circa 1948. (Courtesy of Argonne National Laboratory.)

several mechanical rectilinear manipulators (ref. 74). Models BNL–3 and BNL–4 are typical. BNL–4, for example, controlled the X–Y–Z motions of the hand with cables that moved on overhead carriage in the fashion illustrated in fig. 71. Cables attached to the operator's controls, which were full-sized analogs of the actual hand and arm, also caused rotation of the vertical column and motion of the pivoted wrist joint (fig. 72). The features that separated BNL–4 from the earlier Argonne mechanical master-slaves were, first, the X–Y–Z type motions that made it rectilinear and, second, the long cables and many mechanical-advantage pulleys that made it unilateral in fact, though not in theory. Although this kind of manipulator is not generally called a master-slave, the "arm" and "hand" in the hostile area mimic the motions of the controls, i.e., there is spatial correspondence. Except for the hand, the BNL–4 manipulator has few anthropomorphic characteristics. Finally, it is obvious that only the addition of electric drive motors is necessary to convert this type of manipulator into the bridge-crane electric unilateral models so common today.

Mechanical Master-Slaves

The mechanically linked master-slaves developed by Argonne National Laboratory and General Electric under AEC auspices in

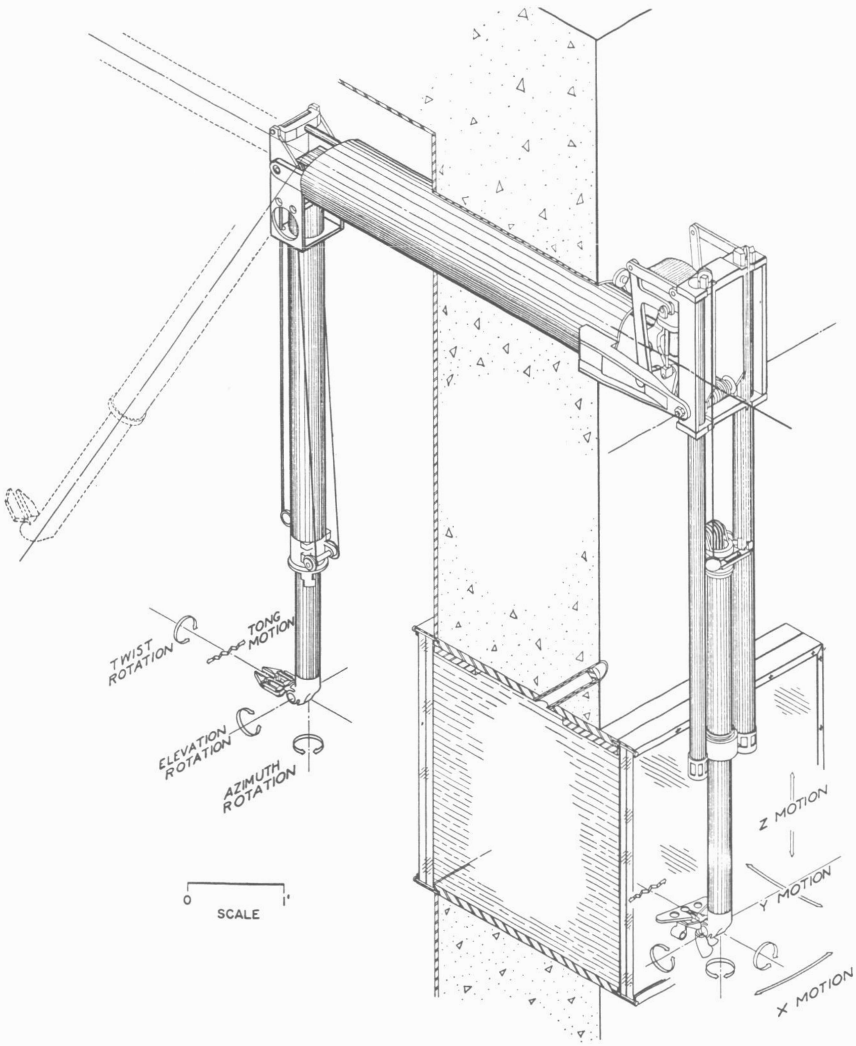

FIGURE 75.—Installation drawing of an ANL Mod–8 mechanical master-slave, showing typical suspension of arms from horizontal support tube.

the late 1940's were major advances in teleoperator technology. These master-slaves had arms and hands that looked rather like human arms and hands. The friction in the cable linkages was reduced to the point where the operator could feel what was going on in the various degrees of freedom.

The ANL Model M1 was the first manipulator built along these principles (ref. 75). Replacing the ball-swivel is an over-the-wall tube suspended from a counterbalanced hinged support (fig. 73). The rectilinear X–Y–Z motions of the overhead movable carriage have in effect been replaced by angular and sliding motions like those seen in the ball-swivel tongs—only with the hands offset by the length of the vertical arm—and with the "swivel" now able to move along a vertical arc as the operator lifts the whole counterbalanced assembly. The three wrist degrees of freedom and the grip degree of freedom are communicated by means of cables running through the supporting overhead tube of the M1. Cable paths are short and friction low enough so that forces are reflected, and the machine is bilateral in fact as well as principle (fig. 74). Note that the M1 and the mechanical master-slaves covered below do not have "elbow" joints.

The biggest problem with the ANL M1 was that it was restricted to hot cells without ceilings because of the movable over-the-wall support tube. Its load rating, moreover, was only about one pound. Radioactive sources soon became so powerful that ceilings had to be put on hot cells to prevent radiation, streaming through an open top, from being reflected back down onto operating personnel. Subsequent ANL mechanical manipulators worked first through a hole in hot cell ceilings and finally through horizontal tubes high in the hot-cell walls—the present arrangement of most mechanical master-slaves in the nuclear industry. Later Argonne models, such as the Model M8, have load capacities of up to 25 pounds.

The ANL Model M8, or Mod 8, as it is often called, became the standard hot-cell manipulator in the 1950's and it still is. Commercial concerns, such as Central Research Laboratories and AMF Atomics have manufactured thousands of manipulators built around the basic ANL Mod–8 configuration.

In the Mod 8 (fig. 75) a fixed horizontal tube supports both master and slave arms, which are pivoted at either end of the tube. The tube can rotate, but not slide back and forth, through a concentric tubular support built into the hot-cell wall. Up-and-down motion along the length of the arms is accomplished by tape-controlled telescope action on the slave end, a distinctly non-anthropomorphic movement. The four degrees of freedom associated with the hand are also communicated through metal tapes or cables running over a system of pulleys. Mod 8, like the M1, is bilateral in seven dimensions.

Despite the great advances inherent in the Mod–8 design, an operator can only work about one-sixth as fast with it as he can with his bare hands. Manipulator operation is tiring, too, not only because of inertia and friction at the operator's wrists but

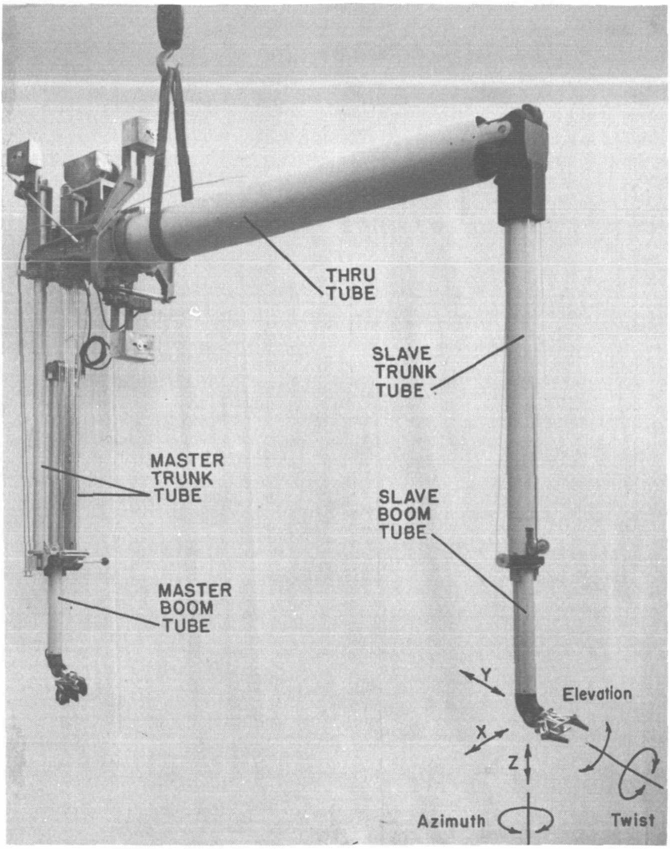

FIGURE 76.—A CRL Mod–8 mechanical master-slave. (Courtesy of Central Research Laboratories.)

also because staring intently through a thick shielding window is a severe strain, no matter how well-trained the operator. Nevertheless, much high-radiation-level hot-cell work is being done with the help of the Mod 8 and its many close cousins.

The Mod 8 has its weak points: cables stretch, wrist-joint gears fail, and there is some cross coupling between different degrees of freedom. These problems have been overcome to some extent by commercial manufacturers. Companies such as Central Research Laboratories and AMF Atomics also have added extended-reach capability, squeeze alarms (to protect delicate objects), gas-tight seals, and other refinements. However, it is interesting that there have been no *major* changes to the basic Mod–8 design (fig. 76) since its introduction in 1954.

The Mod 8 is really a rather complex machine. Figure 77a

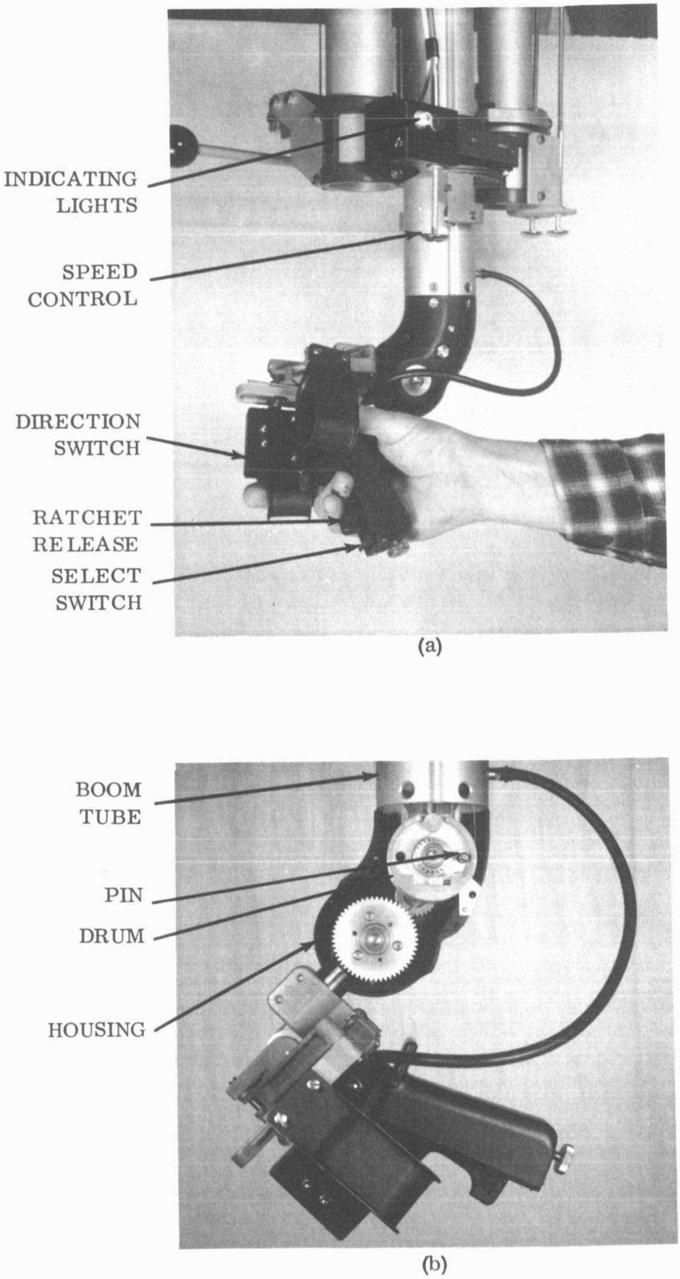

FIGURE 77.—Master hand of a CRL Mod–8 mechanical master-slave. (a) Fully assembled hand, showing wrist, finger controls for grasp, and various other lights and switches. (b) Hand dissembled, showing wrist gearing and tape drum. (Courtesy of Central Research Laboratory.)

shows the CRL control hand as it appears to the operator, while fig. 77b portrays the master wrist gearing that transmits the operator's applied forces to the metal tapes connected to the slave wrist. One of several possible tube mounting approaches is shown in fig. 78. Note that the top of the AMF master arm has counterweights installed and that the tube piercing the hot-cell wall may contain various quantities of shielding material. In fig. 79, we see the slave end of a Mod 8 along with an array of different "tongs" or fingers that may be mated to the tong adapter. Lastly, to show the maze of cables and tapes needed to transmit operator commands in seven degrees of freedom to the slave arm and hand, fig. 80 presents the general cabling and tape schematic for a Mod–8 master-slave.

The Mod 8 is a workhorse of the nuclear industry, but it is not suitable for all applications. Some operators, particularly in chemical and in vacuum-chamber applications, can get along quite

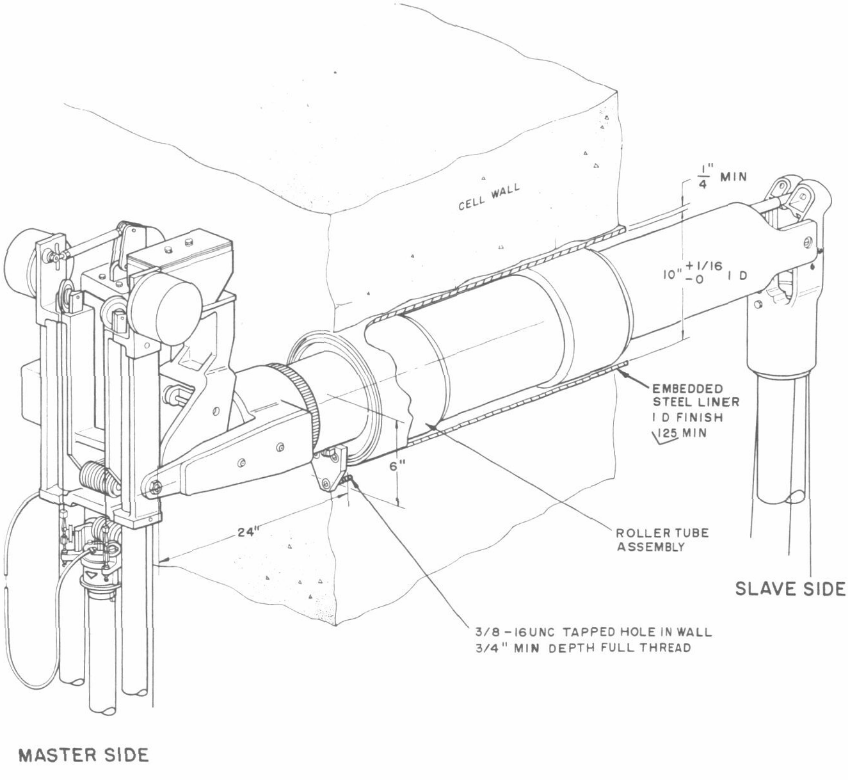

FIGURE 78.—The "roller-tube" mounting scheme for a AMF Atomics Mod–8 mechanical master-slave. (Courtesy of AMF Atomics.)

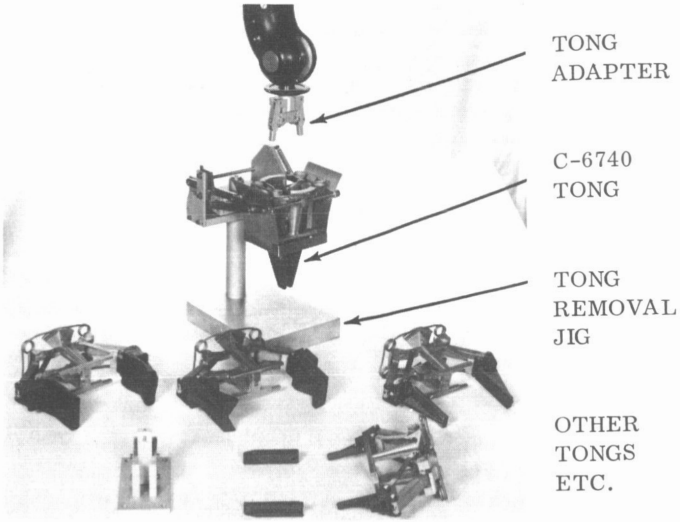

FIGURE 79.—A CRL Mod-8 tong adapter, showing the various types of hands that may be used on this mechanical master-slave. (Courtesy of Central Research Laboratories.)

well with smaller, less-sophisticated master-slaves. Manipulator manufacturers have responded to this need with smaller master-slaves, such as the AMF Mini-Manip.*

The Mod 8's are mechanically connected machines and master and slave ends cannot be separated by the distances or leak-proof barriers characteristic of the space and undersea application areas. The ANL electrical master-slaves, which are described later in this chapter, overcome this deficiency. Central Research Laboratories have also built gas-tight seals for the Mod 8, in which tape motion is converted to rotation at the sealed barrier and back into tape motion on the other side.

Wearer-Actuated Prostheses

For artificial limbs the criteria of design excellence are quite similar to those applied to all other teleoperators, the major exception being the property of cosmesis, i.e., looking and sounding human.

The mechanically connected prostheses introduced here are actuated by musclar action of the wearer. Because of the rigid connections from muscles to the artificial limb and vice versa,

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*The AMF Mini-Manip is not a true master-slave because the Z-direction of motion is reversed between master and slave ends.

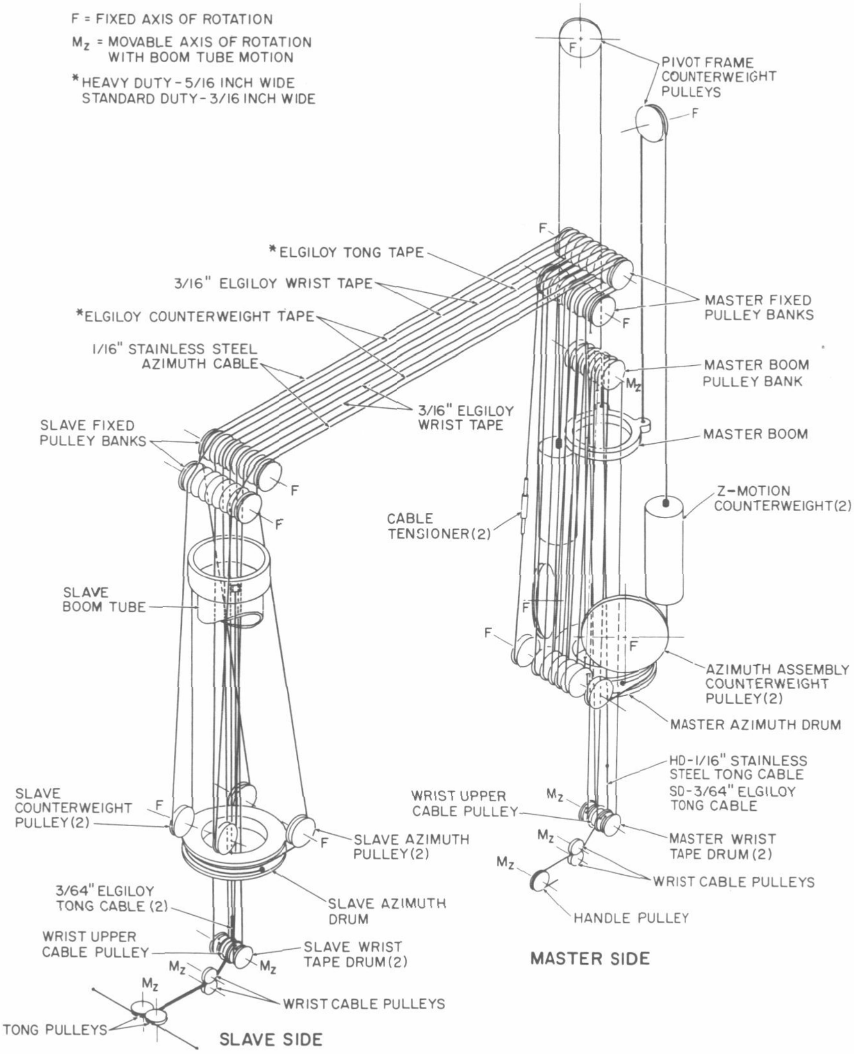


FIGURE 80.—General cabling and taping schematic of the AMF Atomic Mod–8 mechanical master-slave. (Courtesy of AMF Atomics.)

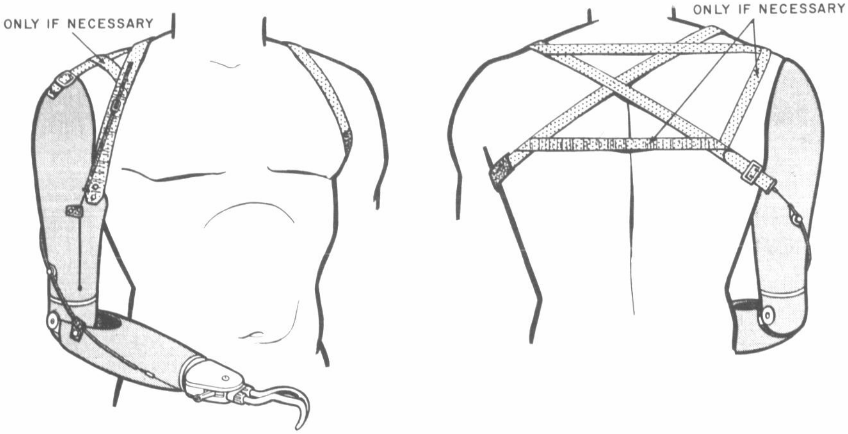
these prostheses are bilateral in the sense that an external force on the artificial limb is communicated through thong and cable to the activating muscles. Although the artificial limb is certainly anthropomorphic, a prosthesis cannot be called a master-slave device because the master end is not a physical analog of the slave end.

Distinctions among wearer-actuated artificial hands, arms, and legs depend mainly upon how much of the human body is to be replaced by the machine (ref. 76).

Artificial hands are divided into "hands" and "hooks." Hooks are the simplest and most common of the so-called "terminal devices" (ref. 77). They are analogous to the vise-type of manipulator hand. A typical hook (fig. 68) may show little effort at cosmesis. Some hooks are normally closed by spring action and open when actuated by the wearer; these devices have only the grip of the spring. The "voluntary-closing" hooks are also popular and are made in many sizes and shapes.

Most hooks depart from parallel vise action. For example, the Dorrance No. 5 hook opens and closes along an arc so that the open "jaws" are canted by about 20°. All hooks, as well as the hands described below, are actuated by a single cable attached to a harness worn by the amputee or to one of his muscles by a surgical process called "cineplasty." Closing forces are only three or four pounds on the average (fig. 81).

Designers of artificial hands (as opposed to hooks) have tried to humanize the machine. Hand engineering is still restricted by the availability of only a single control cable. This pull force must be transplanted into a hand-closing action that not only looks natural but helps the wearer do something useful, such as feeding himself. Originally, prosthetics engineers believed that curved fingers and thumb, closing in a fist-like action, would be



ABOVE-ELBOW "FIGURE 8" HARNESS

FIGURE 81.—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.)

the most useful. Experience soon proved that most manipulation is done with "palmer prehension" using only slightly curved fingers and an almost straight thumb, as in handling table utensils (ref. 78). The engineering problem thus became one of moving fingers and thumb into this configuration with a single cable. Hundreds of attempts have been made to render the human hand in machine form for the benefit of amputees, using an amazing array of ingenious linkages that create varying coordinated grasping actions of fingers and thumb. The APRL No. 4 hand, designed by the Army Prosthetics Research Laboratory, is representative of these efforts (fig. 82). The APRL hand includes a cam-quadrant clutch, automatic locking, and three-jaw-chuck prehension (thumb and first two fingers). Other hands actuate all four fingers and the thumb, too; some boast articulated fingers. However, in prosthesis design, as in most engineering, simplicity is a powerful advantage.

A problem common to artificial hands and manipulator hands is force multiplication. An operator (or wearer) may wish to exert more squeeze than the normal actuating mechanism permits. Engineers introduced force multipliers that give the operator a mechanical advantage whenever an object is encountered by the closing hand. Added force is purchased at the price of greater displacement of the control cable. One of the force multipliers designed for use in prosthetics is illustrated in fig. 83.

The main function of an artificial arm is identical to that of a manipulator arm: To move the hand to the desired position in space and orient it. Unfortunately, the wearer of an artificial arm cannot bring into play the many control cables typical of the hot-cell manipulator. About all he has at his disposal is shoulder shrug, shoulder elevation, residual motion of the arm stump, and

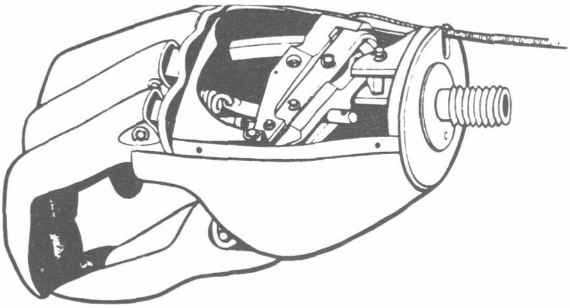


FIGURE 82.—The APRL No. 4 artificial hand with top cover removed. First and second fingers are pulled toward a two position thumb. Third and fourth fingers are floating (ref. 76).

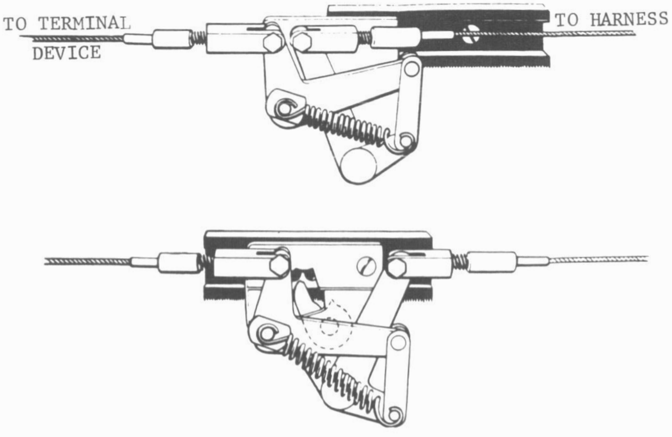


FIGURE 83.—One type of force multiplier. When the finger tips of an artificial hand feel the resistance of an object, the force multiplier increases the mechanical advantage (ref. 76).

perhaps muscles brought into play by cineplasty. Although these motions can be used to power an artificial arm, the wearer cannot force his prosthesis to approach the proficiency of the normal human arm or even a master-slave.

There are so many types of upper-extremity amputations, that Klopsteg and Wilson (a key reference in this field) prepared a table (ref. 76) showing lost functions and how they may be partially recovered through application of machines. We reproduce it here with slight modifications (table 15).

The Northrop wrist-flexion referred to in table 15 is not continuously controllable by the amputee; it is rather a hinged wrist that can be moved (by the other hand) into one of several fixed positions. This can hardly be classed as a teleoperator, despite its great utility to the amputee. The same comment applies to the devices permitting rotation of the forearm or wrist; the step-up units and the F–M (Fletcher-Motis) disconnects are all manually operated devices that permit the amputee to lock the wrist or forearm at various rotational positions and, in the case of the disconnect, change hands. Humeral rotation, elbow flexion, and elbow stabilization devices fall into the "manual" category, too, in that they are not under continuous control by the wearer. In this sense, they are like the locks on mechanical manipulators with which the operator can manually immobilize a degree of freedom.

Elbow flexion, an obvious and very desirable motion to try to mechanize, can be accomplished by providing a hinged artificial limb, a harness, and a cable that lifts the arm up when the shoulder is shrugged and/or the stump is flexed. A harness-actuated elbow lock is usually provided in artificial arms of this type. Elbow lift is second in importance only to hand action. These are the only two motions that are commonly mechanized in wearer-actuated artificial arms.

Walking, too, is a human function amenable to mechanization with artificial limbs. The wearer of an artificial leg, however, usually does not manipulate his man-made leg save for moving his stump during the walking process. The artificial limb "steps off" and "swings" through a sequence of motions similar to those of the natural leg without any actuating cables whatever. True, a control cable may be employed by the wearer to lock the knee joint, but the amputee does not ordinarily manipulate anything.* Reluctantly, we have to exclude artificial legs and all their ingenious mechanisms from that class of teleoperators called "walking machines," but the manipulator and prosthesis industries have much to learn from each other.

HYDRAULIC TELEOPERATORS

Wherever the operator cannot actuate a teleoperator directly by cables, tapes, or rigid linkages, hydraulic or electrical actuators are substituted to convert command signals into the desired forces and motions. Table 16 summarizes the various types of hydraulic teleoperators.

Hydraulic actuators are comparatively powerful per unit weight and amenable to easy force multiplication. They have been made reliable after many decades of industrial use. But, they are also leaky and prone to drift. Pneumatically actuated teleoperators are apt to be spongy; their hydraulic cousins are often sluggish. For applications where strength and compactness are assets, as in walking machines and exoskeletons, however, hydraulic actuators have no peers.

Pneumatic Prostheses

Engineers have tried to adapt external power sources to artificial limbs because wearer-actuated prostheses are weak, usually uncomfortable, and require a great deal of energy. The most popular power source is a small steel capsule filled with liquid carbon

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*Some proposed artificial legs store energy (say, as pressurized gas) gathered in one phase of the walking cycle and then release it during another, viz., in "step off."

TABLE 15.—*Mechanisms for Restoring Lost Bodily Functions.*

Type of amputation	Function							
	Shoulder movement	Upper-arm flexion, abduction, adduction	Humeral rotation	Elbow stabilization	Forearm flexion	Forearm and wrist rotation	Wrist flexion	Hand prehension
Wrist disarticulation	Normal	Normal	Normal	Normal	Normal	Normal	....	Pull-cable and terminal device
Long below-elbow	Normal	Normal	Normal	Normal	Normal	Normal	Northrop wrist-flexion unit	Pull-cable and terminal device
Medium below-elbow	Normal	Normal	Normal	Normal	Normal	Northrop or APRL step-up unit	Northrop wrist-flexion unit	Pull-cable and terminal device
Short below-elbow	Normal	Normal	Normal	Robin-Aids lock, if necessary	Hosmer step-up hinge, if necessary	Northrop or APRL step-up unit	Northrop wrist-flexion unit	Pull-cable and terminal device

Elbow disarticulation	Normal	Normal	Normal	APRL hinge-lock elbow	Pull-cable from shoulder shrug	F-M disconnect	Northrop wrist-flexion unit	Pull-cable and terminal device
Standard above-elbow	Normal	Normal	Normal	Hosmer or Northrop elbow	Pull-cable from shoulder shrug	F-M disconnect	Northrop wrist-flexion unit	Pull-cable and terminal device
Shoulder disarticulation	Normal	....	Turntable of elbow (manual)	Hosmer or Northrop elbow with nudge control	Pull-cable from shoulder shrug	F-M disconnect	Northrop wrist-flexion unit	Pull-cable and terminal device
Interscapulothoracic	....	....	Turntable of elbow (manual)	Hosmer or Northrop elbow with nudge control	Pull-cable from shoulder shrug	F-M disconnect	Northrop wrist-flexion unit	Pull-cable and terminal device

TABLE 16.—*Characteristics of Hydraulic and Pneumatic Teleoperators.*

Type of teleoperator	Signal	Unilateral?	Bilateral?	Master-Slave?
Pneumatic prostheses	Mechanical, electric	Yes	No	No
Forging and heavy duty industrial manipulators	Hydraulic, mechanical	Yes	No	No
Hydraulic master-slaves (Hydroman)	Hydraulic	No	Yes	Yes
Electrohydraulic undersea manipulators	Electric	Yes	No	No
Electrohydraulic master-slaves (Handyman)	Electric	No	Yes	Yes
Exoskeleton man-amplifiers (Hardiman)	Electric	No	Yes	Yes
Walking machines	Electric	No	Yes	Yes

dioxide. High-pressure gas from a reducing valve develops power in an artificial limb when admitted to a piston, bellows, braided expanding sheath (McKibben muscle, fig. 84), or a diaphragm actuator. All of these actuators generate linear forces and displacements, simulating to some degree the action of a real muscle (fig. 85). Torsional devices that convert gas pressure into rotation are also available (ref. 79). Activation of any of these actuators may be through a manual valve or an electric switch that trips a solenoid-operated valve. Control of a pneumatic arm can be made less obvious with the use of capacitance touch-switches or photocell switches. Although pneumatic arms are spongy or "soft" and difficult to control precisely, these defects may be eliminated to some degree by going to higher pressures.

The liquid CO_2 capsule is convenient but it does not usually store sufficient energy to enable an amputee to walk with an artificial leg. So far, pneumatic prostheses have been confined to upper extremities. Pneumatic power has also been applied to orthotic devices.

Hydraulically actuated arms and legs are possible, but they require the amputee to carry a power source, a pump, and all the

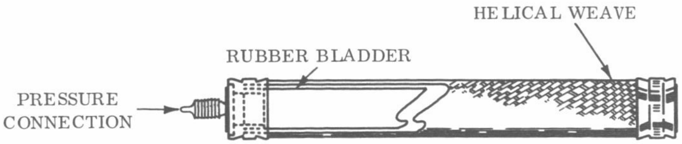

FIGURE 84.—The McKibben artificial muscle. Application of pressure causes the braided fabric to bulge out and pull the ends of the muscle closer together.

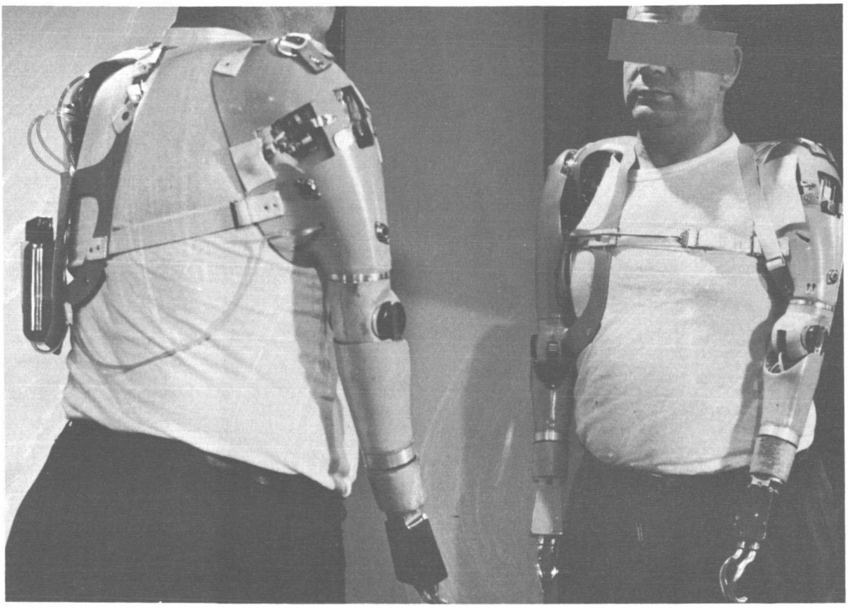
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FIGURE 85.—The AIPR pneumatic prosthesis. (Courtesy of E. Murphy, U.S. Veterans Administration.)

requisite plumbing around with him. Nevertheless, electrohydraulic arms using water and employing hydraulic servo motors have been successfully constructed (ref. 80).

Heavy-Duty Manipulators

The heavy-duty manipulators employed in metal-treating plants and other operations where heavy, hot objects must be handled with a modicum of dexterity are similar to the pneumatic and hydraulic artificial arms just described. Hydraulic actuation is used in missile loaders, bulldozers, forklifts, and other heavy industrial handling equipment. But the great majority of these aids are not members of the teleoperator family because their manipulatory capabilities are far below those of a human being (ref. 81).

At least two small submersibles have carried all-hydraulic manipulators controlled directly by manually operated valves. These were the *Recoverer I* and the *Diving Saucer SP–300*. Later submersibles almost invariably have relied on electrical and electrohydraulic manipulators which do not compromise hull integrity with large hydraulic line penetrations.

Hydraulic Master-Slaves

All-hydraulic, bilateral master-slaves with several degrees of freedom are rather rare animals in the world of teleoperators. Single degrees of freedom using hydraulic actuation are much more common, particularly when a strong gripping force is wanted with tongs or other mechanical manipulators. Such a hydraulic hand is illustrated in fig. 86. Because friction can be made low and master and slave pistons have approximately the same areas (no mechanical advantage), force and motion are transmitted in both directions; thus, the device is truly bilateral.*

The Hydroman, built by Oak Ridge National Laboratory, repre-

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*The GE Hardiman is an all-hydraulic exoskeleton. It is described later in this chapter.

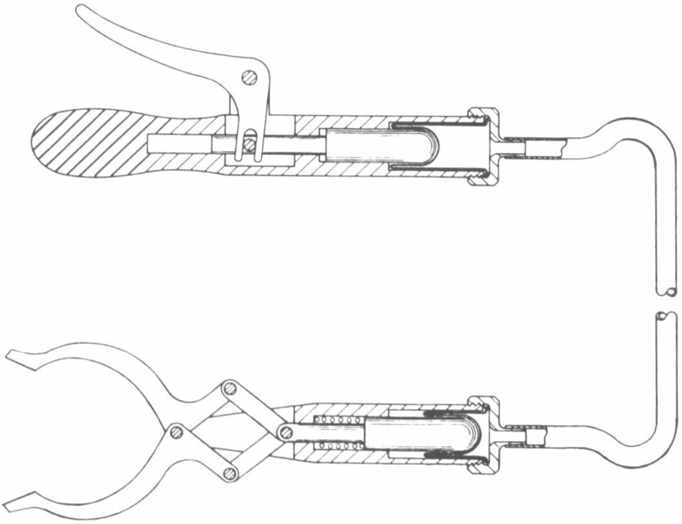

FIGURE 86.—A hydraulic grip device developed by Brookhaven National Laboratory for use with tongs and other mechanical manipulators. Force feedback exists here.

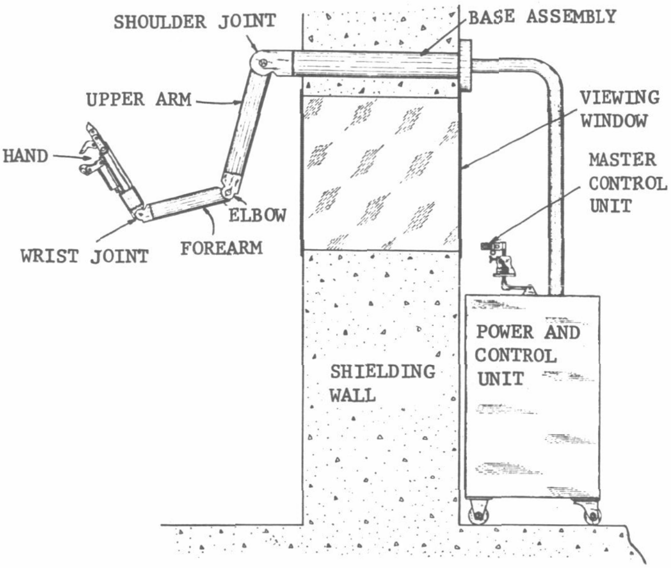

FIGURE 87.—The Oak Ridge Hydroman was an all-hydraulic, heavy-duty manipulator with force feedback. See fig. 57 for the hydraulic control schematic (ref. 81).

sents one of the few attempts to construct an all-hydraulic teleoperator (fig. 87). Hydroman was built for through-the-wall hot-cell operations involving heavy loads. Hydroman was given an elbow but no up-and-down telescoping action. The forearm delivered 1000 in.-lb of torque from an internal, reversible hydraulic motor. The wrist joint was a hydraulic cylinder with a rack and gear assembly to convert linear motion into rotary motion. Force reflection or feel is not transmitted back through the power loop, as in the gripping device in fig. 86, but through a differential feedback cylinder (see fig. 57) and a feedback force-ratio bar. Thus, Hydroman can be classified as bilateral. Hydroman is not a true master-slave because there is no spatial correspondence, but natural motions of the operator's arm and hand are communicated to analogous manipulator components through the hydraulic linkages.

Electrohydraulic Undersea Manipulators

The combination of electrical command signals and hydraulic actuation is logical for small submersible manipulators. Hydraulic actuators perform well in high pressure seawater and can be assigned heavy tasks. Seawater itself has been used as the hydraulic fluid for some devices such as the NEL (Navy Electronics Laboratory) manipulator. As technical interest and research and development money have flowed increasingly into undersea work, more and more innovations in the teleoperator art have come from this area.

Early undersea manipulators were either electrical unilateral machines (on *Alvin I,* the *Trieste,* and the RUM bottom crawler) or all-hydraulic (on the *Discoverer I* and *Diving Saucer SP–300*). The electrical manipulators were modified General Mills Model-150 terrestrial machines. These worked, but proved "delicate" and rather vulnerable to the deepsea environment. Excellent results were obtained with the all-hydraulic manipulators in shallow water. Their large hull penetrations, however, would be risky at great depths. Many new submersibles use electrohydraulic teleoperators.

Hunley and Houck, in their 1965 review of underwater manipulator technology (ref. 82), noted that:

1. Two manipulator arms are desirable in underseas work because of the complex tasks.
2. In working manipulators (as opposed to specimen-collecting types), many degrees of freedom are desirable, especially wrist extension.
3. Provision for emergency jettison of the manipulator is desirable (a feature militating against all-hydraulic systems), and the jettison mechanism should not be such that manipulators may be dropped inadvertently or lost if they are not stowed properly. (Manipulators were lost at sea in early development work.)
4. Some way to confirm proper manipulator stowage is desirable.
5. Hard stops and/or limit switches of some kind are needed to prevent structural damage, even if there are slip clutches and pressure-relief valves in the system.
6. Internal leakage must be kept low to prevent drift or "creep" of the manipulator actuators.
7. External wires and hydraulic lines must be kept to a minimum because of high drag forces during vehicle towing and the possibility of entanglement with debris around some work areas.

Undersea electrohydraulic manipulators tend to be larger and more rugged than their terrestrial counterparts (figs. 88 and 89). Another common feature is the square or rectangular, rather than circular, cross section of the arms, a characteristic resulting from

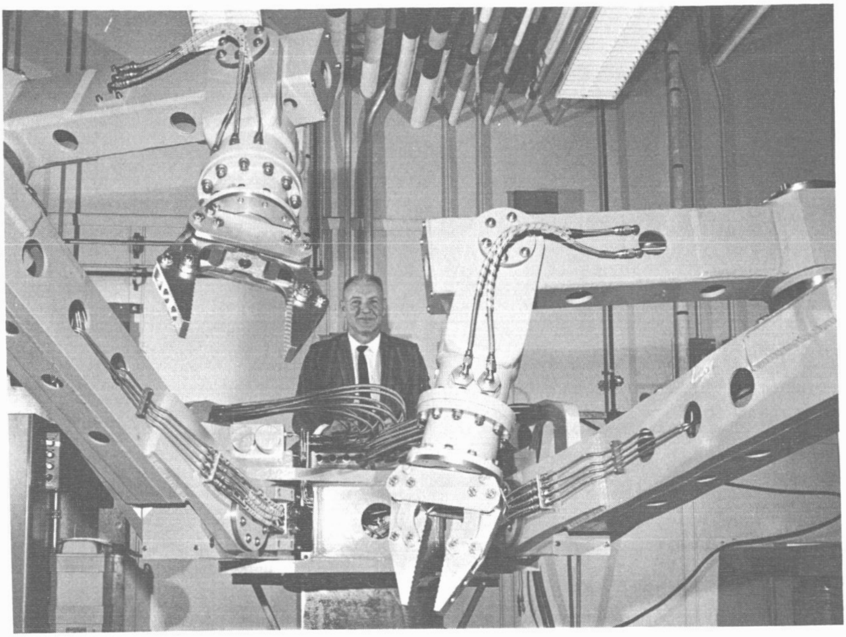

FIGURE 88.—The General Electric electrohydraulic unilateral manipulator built for the *Aluminaut.* Note the hydraulic lines and the "battleship" construction. (Courtesy of General Electric Co.)

such desiderata as easy fabricability and accessibility, and the desire to enclose wires, hydraulic lines, transducers, and actuators.

Hot-cell manipulators are usually suspended from an overhead support in such a way that the operator can view the hands at roughly eye level. Undersea manipulators, in contrast, are often mounted on one side of or below the operator within the submersible (fig. 89). The arms are projected out horizontally rather than suspended vertically. Undersea arms almost invariably have shoulders, elbows, wrists, and, predictably, hands. One degree of freedom per joint seems the rule, and wrist motion is usually more limited than that in a mechanical master-slave. In other words, the arms are well articulated in order to maneuver the hand into position but the joints have fewer degrees of freedom. The wrist often has only two rather than the more common three degrees of freedom.

As this is written, many unilateral electrohydraulic manipulators, but no electrohydraulic master-slaves, have been built for undersea use, although the latter are well within our engineering

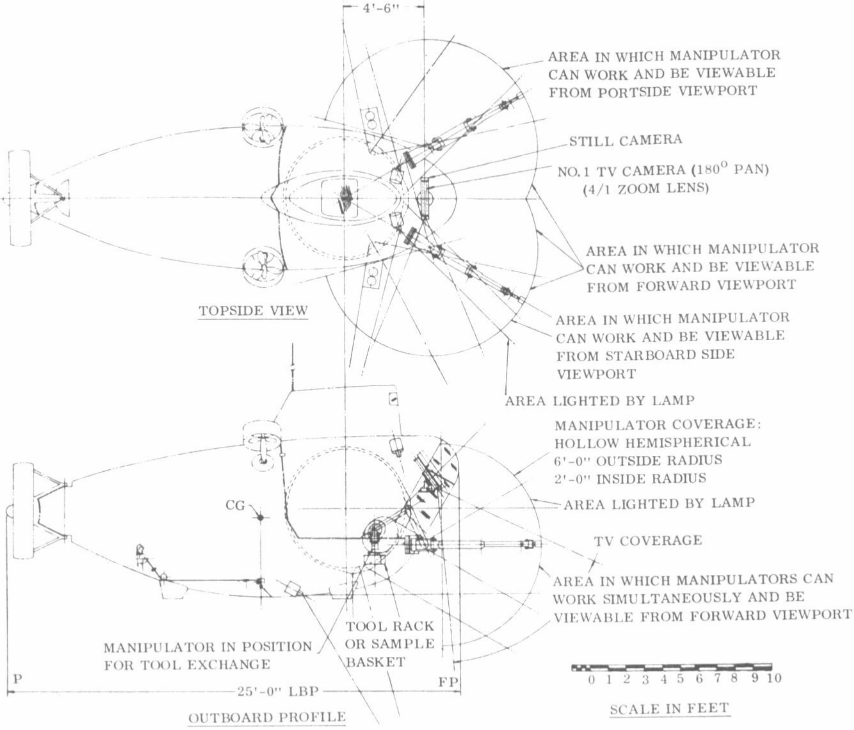

FIGURE 89.—Manipulator installation aboard the *AUTEC–I* submersible. Vehicle and manipulators were built by Electric Boat Division of General Dynamics (ref. 83).

capabilities. Several companies are studying them. None of the present undersea arms possesses force feedback that would place it in the bilateral category. Some do have position feedback that assures the operator that the arm possesses the same configuration as the replica he employs as a control device (see chapter 4). The Electric Boat Division of General Dynamics has developed a "prosthetic" arm control that forces the manipulator arm to take on the same configuration as the operator's arm. Since there is configuration correspondence, one is tempted to assign such a teleoperator the designation master-slave. (Note that configuration correspondence does not insure spatial correspondence because an undersea arm is usually much larger than the control arm, meaning that linear velocities are not the same, even though angular velocities are.)

The arm joints pictured in figs. 88 and 90 are all rotary. Since hydraulic actuators (pistons) are nearly always linear in their

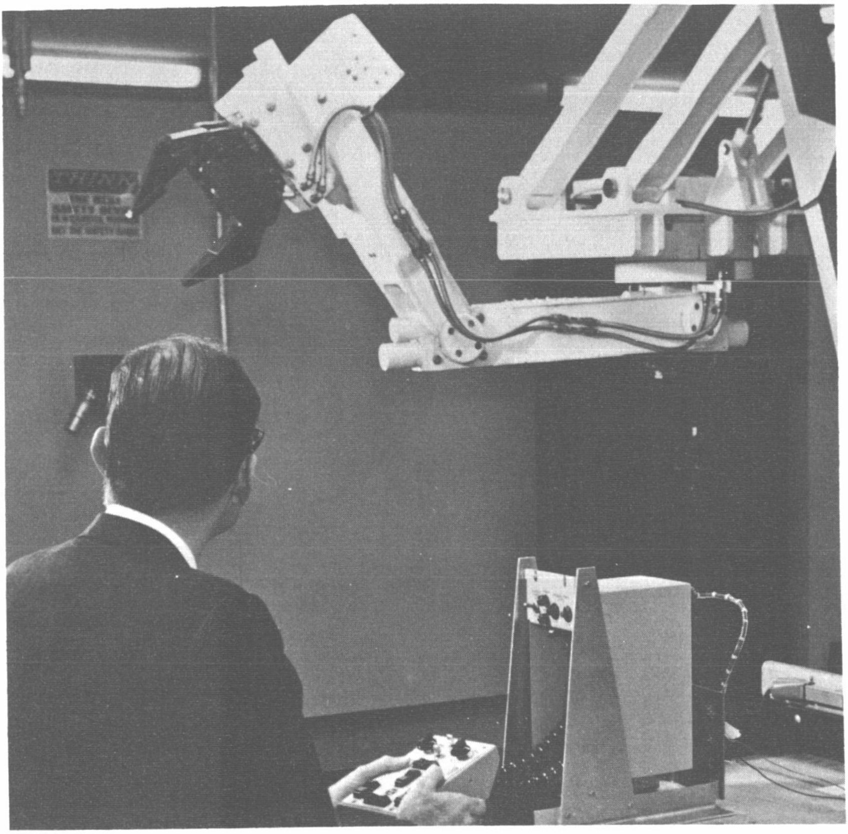

FIGURE 90.—The Westinghouse Model–200 underseas electrohydraulic manipulator. It can lift up to 500 lbs and rotate any of its joints at speeds from 0° to 18° per sec. This model possesses six degrees of freedom. (Courtesy of Westinghouse Electric Corp.)

action, a rack-and-pinion mechanism is required at the joint. These hydraulic pivots are so common that we illustrate a typical actuator arrangement that provides for two-way rotation control from within the submersible (fig. 91). Many variations are possible. Other linear-to-rotary actuators are the so-called "roller-chain" and "vane" actuators (ref. 83).

An interesting design feature under development at General Dynamics' Electric Boat Division is modularity. A modular manipulator is built up from a few basic pieces, much like a Tinkertoy construction. Electric Boat can put together 28 different manipulator arms using only six different building blocks. The arms vary in length, degrees of freedom, and load capability (fig. 92). The modular approach can be applied to most electrical and hy-

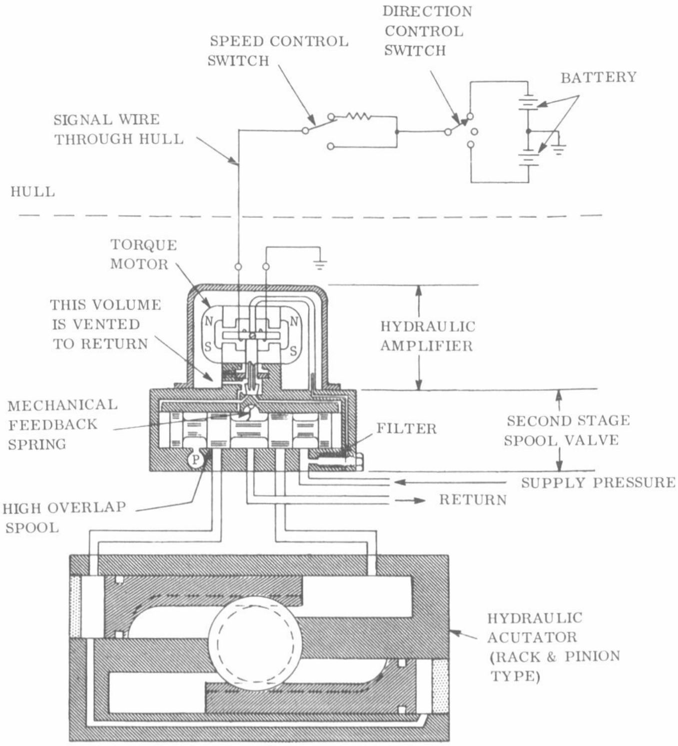

FIGURE 91.—A representative hydraulic pivot actuator employed in underseas manipulators. (Courtesy of Westinghouse Electric Corp.)

draulic manipulators and even to mechanical arms, provided that suitable gear or shaft connections can be made between modules.

The demand for reliable underwater manipulators is indicated by the number of companies working in the area and the variety of hardware produced. The extensive survey conducted by North American Aviation's Ocean Systems Division for the Navy's Deep Submergence Systems Program in 1966 brought together the data presented in table 17 (condensed from ref. 83).

It is impracticable to illustrate or describe all of the manipulators listed in detail. Unlike the situation in the nuclear industry, undersea manipulators are not descendants from the famous Mod 8 or some watery equivalent. A representative installation drawing and a typical electrohydraulic arm will be useful in comparing undersea arms with those in the other application areas. Figure 89 is an installation drawing for the *AUTEC-I* manipulators. These electrohydraulic arms possess eight degrees of freedom apiece: shoulder, 2; elbow, 1; wrist, 4 (including wrist

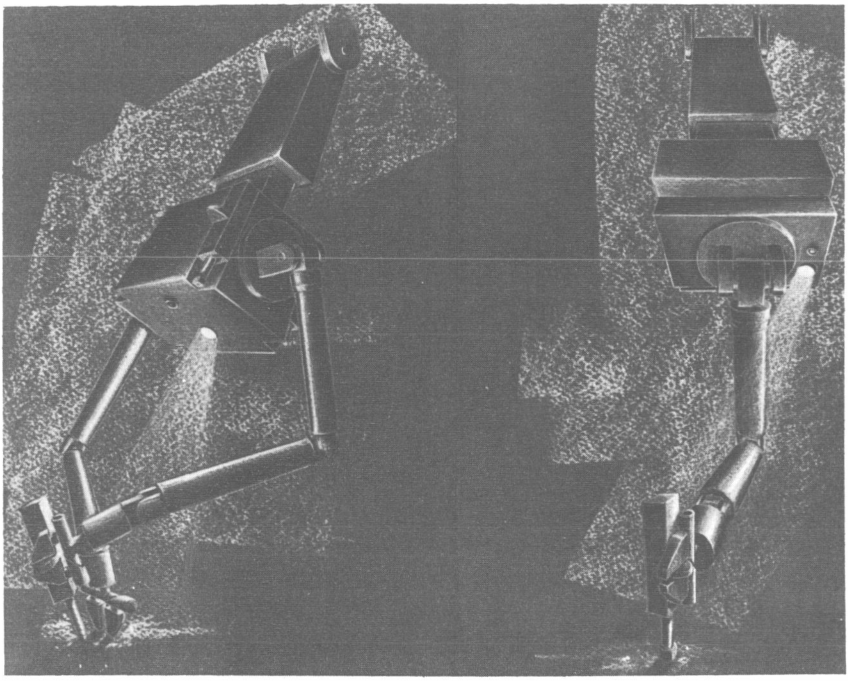

FIGURE 92.—The Electric Boat Modul-Arm manipulator concept incorporates six basic arm units that can be assembled in different ways. (Courtesy of Electric Boat Division, General Dynamics.)

extension); grip, 1. Each arm can exert a force of 50 pounds in any direction. As mentioned earlier, the horizontal extension of the arms under the operator viewport is found frequently on submersibles. In fig. 93, the Ocean Systems Model-2 arm is drawn in top and side views. This arm possesses a total of ten degrees of freedom and a load capacity of 10 pounds. It was designed for the Ocean Systems *Beaver* submersible.

Two other undersea manipulator development efforts have unique features. One is the ten-jointed electrohydraulic arm built by Marvin Minsky's group at M.I.T. (fig. 94). Each of the joints has a single degree of freedom and is actuated by a hydraulic piston. A position transducer parallels the piston to insure that the arm assumes the same configuration as the replica control. This arm will eventually be computer-controlled.

Another development of interest is the so-called "tensor arm," conceived by Victor Anderson, at the Marine Physical Laboratory (MPL) of the Scripps Institute of Oceanography. The basic arm consists of a series of four joints (five links), each with two

TABLE 17.—*Some Characteristics of Underwater Manipulators.*

Manufacturer	Underwater manipulator name or model number	Type	Assigned submersible	Design environmental conditions	Actuator power source	Manipulator-motion control devices	Terminal devices available
Programmed and Remote Systems	150w, 300w, 1000w through 7000w	General purpose. Deisgned and built to specific order.	Various	Max. depth—36,000 ft. Temp. range—50° to 250°F Pressure—18,000 psi Immersion time— Operating cycle—continuous	Oil-hydraulic, water-hydraulic, electric	Switches Position controller	Parallel-jaw hand, hook hand, tong hand, saw
Central Research Laboratories	CRL Model B—canal manipulator CRL Model D—special underwater manipulator	Model B—Standard, off-the-shelf shallow-water master-slave manipulator. Model D—Standard. Both are general purpose.	None	....	Manual electric	Master-slave	Tong tips
General Electric	Manipulator arms for the *Aluminaut* submarine	One-of-a-kind general purpose.	*Aluminaut* submarine	Max. depth—15,000 ft Temp. range—34° to 120°F Pressure—7500 psi	Oil-hydraulic	Switches	....
Litton Industries, Applied Science Div.	ASD Model-162 manipulator	General purpose, underwater environment, designed specifically for *Alvin* vehicle, not a shelf item. Manipulator now in use.	*Alvin* vehicle	Max. depth—10,000 ft Temp. range—28° to 100°F Pressure—4400 psi Immersion time—no limit Operating cycle—continuous	Electric	Toggle switches	3-fingered claw, clam-shell bucket, hook
Westinghouse	OFRS Model No. 2 manipulator	General purpose.	*Deepstar 4000*	Max. depth—4000 ft	Oil-hydraulic	Microswitches	Hydraulic-powered 3-fingered claw

Westinghouse	Model number not yet assigned	Specific purpose: recover small objects, cutting non-metal cable, and making simple cable attachments	*Deepstar 20000* (Tentative)	Max. depth—20,000 ft Temp. range—28° to 80°F Pressure—10,000 psi Immersion time—4320 hr Operating cycle—1 hr in 12	Oil-hydraulic	Switches actuated by depression of bar-type controllers	None
General Dynamics Corp., Electric Boat Div.	HT 7150-400 series	General purpose, off-the-shelf for underwater use. Units in active use as well as in various stages of design, construction and testing. Proven in sub service.	General use	Max. depth—independent Temp. range—20° to 225°F	Oil-hydraulic	Switches, hand-operated valves	....
Koelsch Corp.	Model 122D-1000 (modified standard model 122C)	"Dry" environment model. Proposed for general purpose underwater use—would be built to order.	None	Max. depth— Temp. range— Pressure—3000 psi Operating cycle—	Electric for moving parts, except fingers. Hydraulic for fingers	Solid-state switches	....
Scripps Institute	Benthic Manipulator I	One-of-a-kind manipulator to perform specific tasks in an oil environment underwater. Now in use.	Benthic "Hive"	Depth—200 to 20,000 ft Temp. range—32°F to 150°F Pressure—100 psi to 1000 psi Immersion time—indefinite Operating cycle—continuous Operation in acid—washed kerosene	Oil-hydraulic and electric	Switches, joystick	....

TABLE17.—*Some Characteristics of Underwater Manipulators*—Concluded

Manufacturer	Underwater manipulator name or model number	Type	Assigned submersible	Design environmental conditions	Actuator power source	Manipulator-motion control devices	Terminal devices available
Autonetics	Marine Manipulator Model 1	General purpose. Design complete and prototype tested.	*Beaver MK 1*	Max. depth—20,000 ft Temp. range.—20° to 120°F Pressure—10,000 psi Immersion time—10,000 hr Operation cycle—no limit	Oil-hydraulic	Toggles, push buttons and joysticks, replica arm with: a. Single-speed push button b. Proportional-speed push button c. Position servo	Hook hand, stud gun, grinding wheel, centrifugal pump, wire brush, impact wrench, cable cutter
American Car and Foundry International Underwater Research Corporation	IURC M-600	General purpose, completed	*Trieste II*	Max. depth—10,000 ft Temp. range—30° to 150°F Pressure—5000 psi Immersion time—unlimited	Oil-hydraulic	Individual switches	Finger type
International Underwater Research Corporation	IURC M-100	General-purpose prototype under construction	General use	Max. depth—unlimited Temp. range—0° to 150°F Pressure—unlimited Immersion time—unlimited	Oil-hydraulic	Individual switches	Straight jaw—others in design

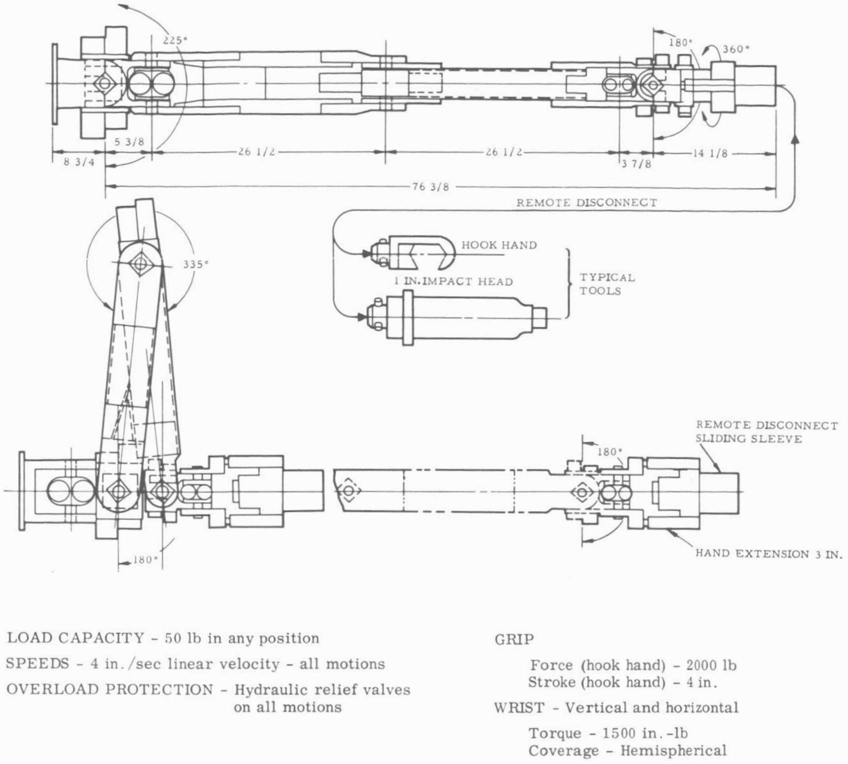

FIGURE 93.—The Ocean Systems Model–2 electrohydraulic manipulator arm designed for the *Beaver* submersible. (Courtesy of Ocean Systems Operations, North American Aviation, Inc.)

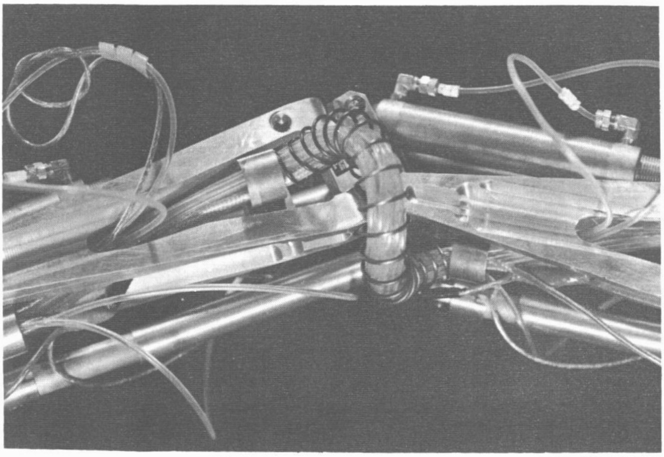

FIGURE 94.—A close-up view of one of the joints of the Minsky electrohydraulic arm. (Courtesy of W. M. Bennett, M.I.T.) (See also fig. 48.)

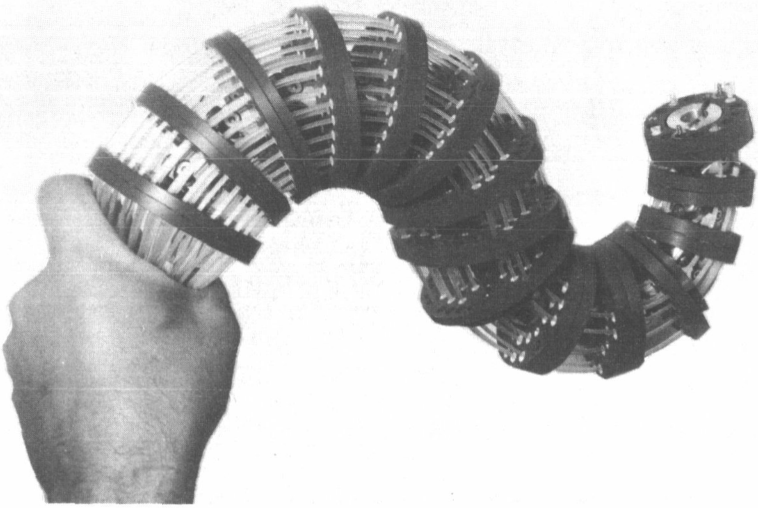

FIGURE 95.—The Scripps tensor arm. Stress on the nylon filaments actuates the arm. (Courtesy of V. C. Anderson, Scripps Institution of Oceanography.)

degrees of freedom (fig. 95). The entire arm is hydraulically actuated by nylon "tendons" strung along the exterior of the arm rather than by actuators placed at each joint. A pull on one side that is not compensated by an equal pull on the other side causes the whole arm to bend in a way similar to the muscle-tendon action in the human arm, except, of course, that the tensor arm possesses two unrestricted degrees of freedom at each joint. Sensor tendons parallel the actuator tendons and give the operator position feedback. The MPL tensor arm, also called Benthic Manipulator II, can operate directly in seawater and is intended for use in the MPL Benthic Laboratory "hive" for replacing electronics cards, wrapping terminals, and so on. In contrast to some of the more massive underwater manipulators just described, the tensor arm is only about 15 inches long. The novel actuation scheme is potentially very important in teleoperator design.

Electrohydraulic Master-Slaves

The General Electric Handyman, like the first Argonne National Laboratory mechanical and electrical master-slaves, represents a milestone in teleoperator technology. Built in 1954 as part of the Air Force/AEC Aircraft Nuclear Propulsion Program (ANP), Handyman embodied a number of unique design features.

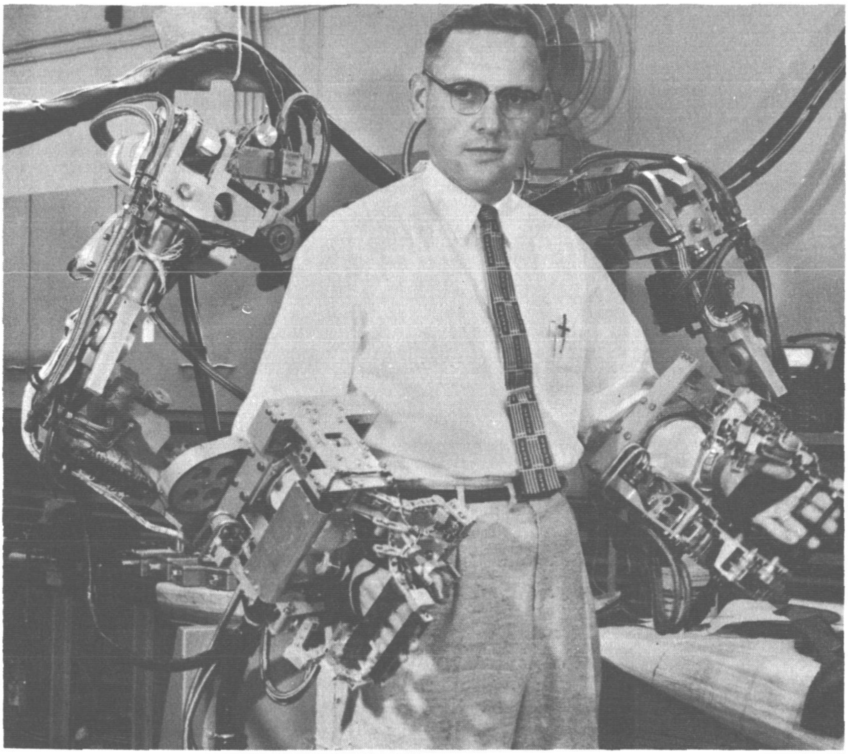

FIGURE 96.—The Handyman master station, with ten bilateral servos in each arm-hand combination. (See also fig. 98.) (Courtesy of R. S. Mosher, General Electric Co.)

Besides being the first electrohydraulic, bilateral master-slave, it was also the first to employ articulated exoskeletal master arms that conform to the operator's arms, as illustrated in fig. 96. Another "first" was the prehensile hand with built-in force reflectors (fig. 97). In overall dexterity and system sophistication, few teleoperators have approached Handyman, but it is a costly and complex machine.

Handyman's dexterity, of course, results from its total of ten bilateral degrees of freedom per arm-hand combination. These are: shoulder, 2; upper-arm twist, 1; elbow, 1; forearm twist, 1; wrist, 1; hand, 4. The Handyman slave arms can lift 75 pounds in their weakest position, i.e., when they are separated the farthest. Each degree of freedom in the slave arm is actuated by an electrohydraulic servo like that pictured in fig. 98. Servo operation begins when a voltage increase causes the torque motor to force the reed nearer the nozzle (ref. 84). Bias pressure then in-

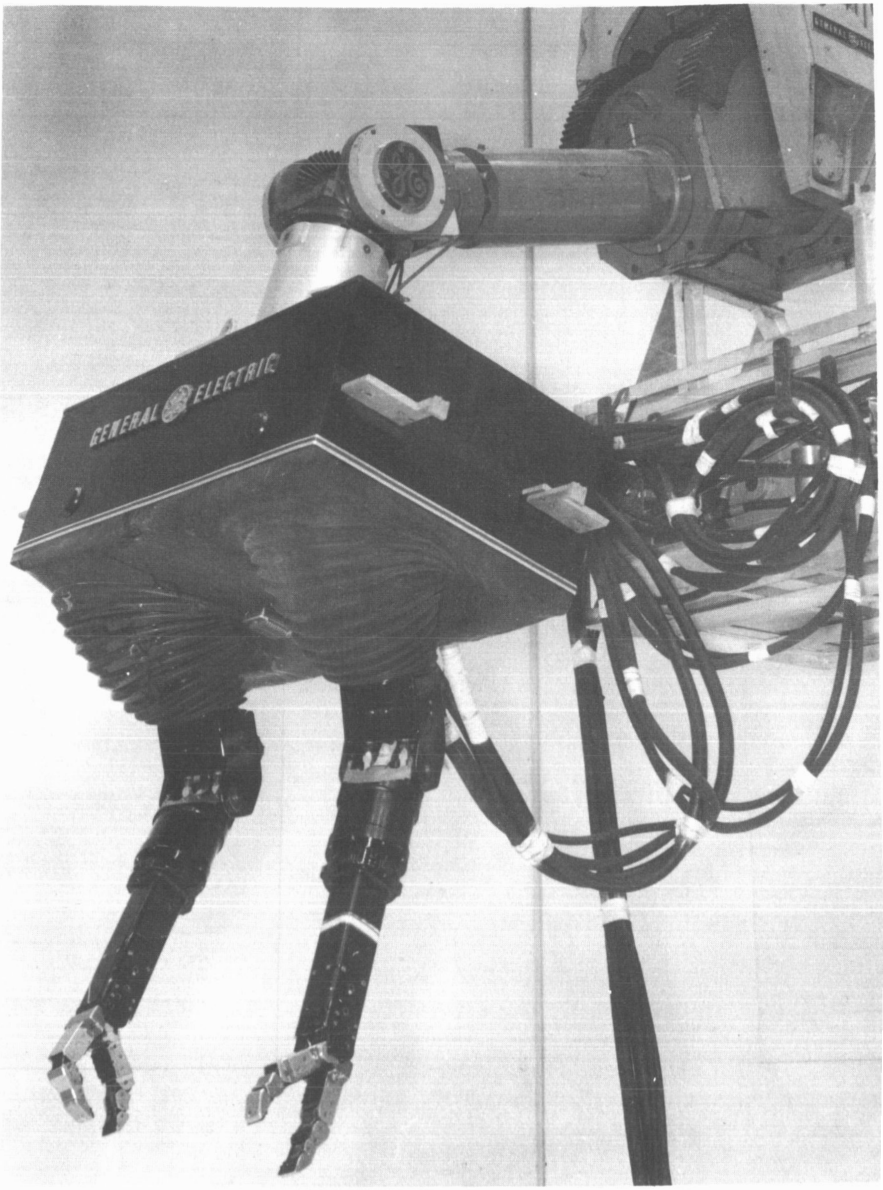

FIGURE 97.—The slave station of the Handyman electrohydraulic master-slave, showing the articulated, independently controlled opposing fingers. (Courtesy of R. S. Mosher, General Electric Co.)

creases, causing the spool to move left. Simultaneously, the control pressure is reduced because some fluid goes to the drain. The control-supply pressure differential then moves the ram to the

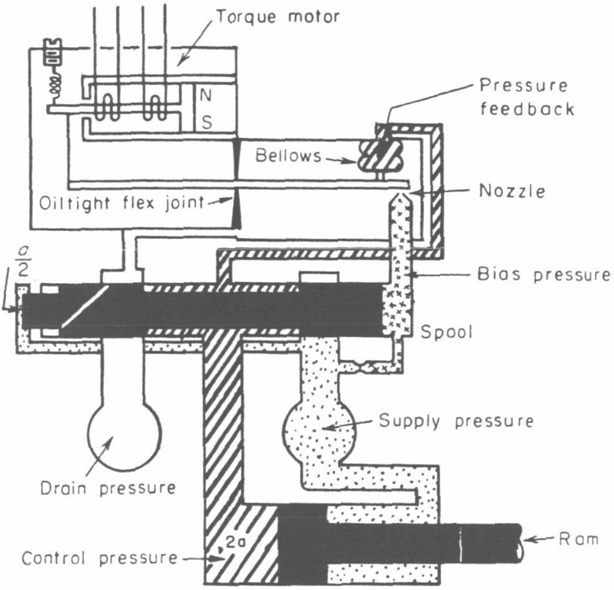

FIGURE 98.—The Handyman modified hydraulic servo with pressure feedback. The ram was packaged with the servo valve in Handyman (ref. 84).

left. At the same time, the decreased control pressure in the pressure bellows allows the reed to move back from the nozzle, thereby causing the ram force to be proportional to the torque motor voltage. Feedback signals are generated by external circuitry (as discussed in chapter 4).

Although Handyman was never used extensively, the technology pioneered during the program has found its way into other teleoperator programs, such as General Electric's exoskeleton work (Hardiman) and walking-machine development programs.

Exoskeleton Man-Amplifiers

Man amplifiers under study and development are either electrohydraulic or all-hydraulic master-slaves that parallel the configuration of the human body. The human operator literally works inside a two-layer mechanical suit. The inside layer consists of a master exoskeleton that follows the more critical motions of the operator whom it encloses. The heavy-duty, outside, slave layer follows the motions of the master exoskeleton that it encases. It is an onion-skin arrangement with man at the core.

Such a man amplifier sounds like a good idea, *but is it technically feasible?* Some of the earliest work on the basic concept was

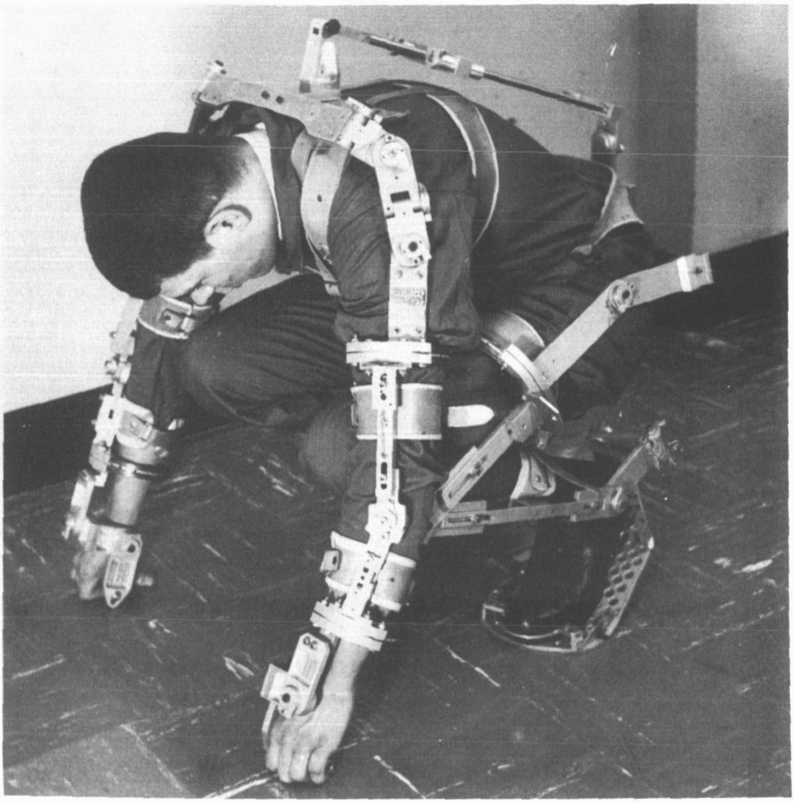

FIGURE 99.—The unpowered exoskeleton model constructed by Cornell Aeronautical Laboratories for exoskeleton structural studies. (Courtesy of Cornell Aeronautical Laboratory.)

carried out at Cornell Aeronautical Laboratory for the Air Force in the early 1960's (ref. 85). These early studies concluded that:

1. Duplication of *all* human motions would be impracticable.
2. Experimentation was necessary to determine just which human motions should be duplicated.
3. Inability to counter overturning moments might limit the load-carrying capability of a man-amplifier.
4. The most difficult problems were in the areas of servo, sensor, and general mechanical design.

Further work at Cornell Aeronautical Laboratory led to the conclusion that a man could be encased in an exoskeleton with substantially fewer degrees of freedom than he possessed himself and still carry out many useful tasks without discomfort. One of the unpowered test exoskeletons is illustrated in fig. 99. Under a contract from the Office of Naval Research, Cornell next undertook to sketch out a preliminary design of the shoulders and arms for a man-amplifier (ref. 86). This study concluded that mobility and dexterity would be adversely affected by the size of the hydraulic rotary actuators unless loads were limited to a few hundred pounds per arm.

More recently, General Electric has advanced the man amplifier concept under a contract sponsored jointly by the U.S. Navy and the U.S. Army (ref. 87).* In October, 1966, General Electric concluded that, although servos are still problems, a powered exoskeleton could be constructed that would enable a man to lift 1500 pounds six feet and carry this load 25 feet in 10 seconds.

In the GE 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" (fig. 100). 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. 101 were selected for each side of the master-slave. With 15 joints on each

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*Part of Project MAIS (Mechanical Aids for the Individual Soldier).

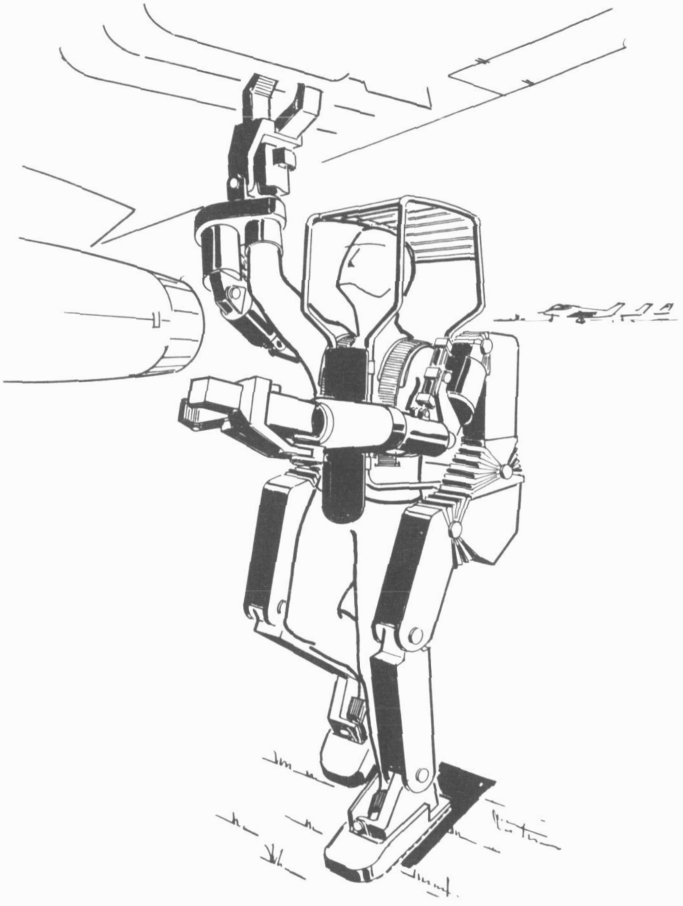

FIGURE 100.—Sketch of the General Electric powered exoskeleton concept (Hardiman I) (ref. 87).

side, a man-amplifier could carry out most of the important human motions, save for those requiring considerable dexterity of the hand. At each joint, except numbers 10 and 12 in fig. 101, hydraulic pistons were the proposed actuators. Hydraulic rotary actuators would alleviate packaging problems at joints 10 and 12. The actuator at each degree of freedom is actually a bilateral servo that reflects forces exerted on the slave members back to the corresponding master member (scaled down by 25), and then to the operator.

To compound semantic confusion, the man amplifier is a bilateral, bilateral master-slave. The first "bilateral" refers to the

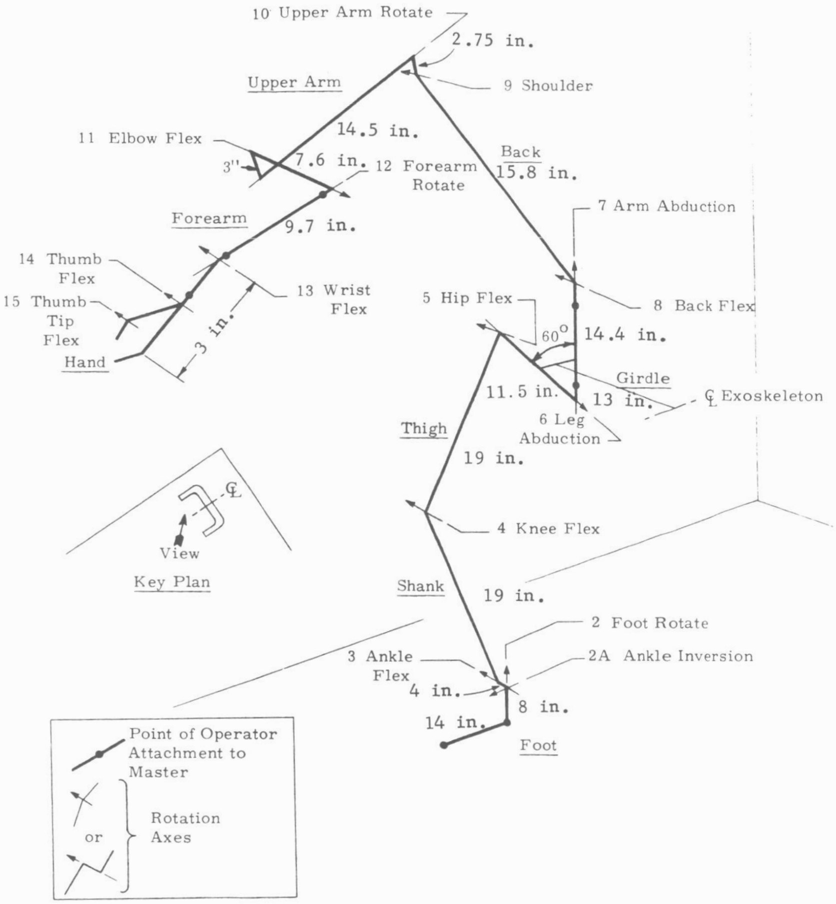

FIGURE 101.—Isometric stick figure showing the kinematic design of one half of the General Electric Hardiman I. There are 15 degrees of freedom (ref. 87).

symmetric geometry of the teleoperator (the "bilateral" from biology) and the second to the two-way flow of motion and force between master and slave.

In the GE concept, the operator exerts a force against the closely fitting control surface at any particular degree of freedom. The surface then moves relative to the encasing slave member and, in doing so, actuates a valve in the master control circuit. The signal is transmitted hydraulically, so that the GE man amplifier is all-hydraulic, somewhat like the Oak Ridge Hydroman.

One of the major problems with this concept as it now stands is power consumption. General Electric estimates that the peak power consumption during normal operations would run as high as 60 horsepower. This quantity of power can be generated by a lightweight gasoline engine or a gas turbine that the man amplifier could backpack with enough fuel for several hours of operation. The weight and bulk of the power subsystem could be substantially reduced if more efficient bilateral servos could be developed. In work areas where power lines are available, man amplifiers could be "plugged in."

Walking Machines

The man amplifiers described above are walking machines, of course, but a machine's legs need not conform to those of a man. They then may be made as large or as small as a task demands. Usually, the master-slave variety of walking machine is larger than a man.

Because of the high loads encountered with such a vehicle, hydraulic actuators predominate in designers' thinking. A walking machine, however, need not be all-hydraulic; the linkage between master and slave may also be mechanical or electrical. In an experimental balance machine, built by General Electric, and shown in fig. 102, the link between operator and actuators was purely hydraulic (ref. 88).

Walking machines have been built without the master-slave relationship between operator and actuator. In walking toys and even the Space-General walking wheelchair (fig. 25), the operator only turns the machine on and off and steers it. In these machines, which are not teleoperators, the feet are preprogrammed to follow a specific motion, regardless of the terrain. William E. Bradley, of the Institute for Defense Analyses, has suggested substituting a computer for a human driver. A computer buttressed with suitable stored information and subroutines plus suitable sensory feedback from the feet and visual sensors could take a walking machine over unpredictable rough terrain. However, as Bradley points out, this would be "a formidable exercise in cybernetics," and much beyond the scope of this book.

Even though General Electric's dynamic balance experiment (fig. 102) proved that a man could easily balance himself atop a servoed two-legged machine, most designers favor vehicles with at least four legs. Even a human falls occasionally and a machine without "hands" or some other aid to regaining its feet would be helpless when it fell. The big advantage of a two-legged walker would be that a single man could operate it with master-slave, force-reflecting leg controls and have his hands free for

FIGURE 102.—The balance machine built by General Electric for the Army Tank and Automotive Center (ATAC). Man's ability to balance a two-legged walking machine was demonstrated with this machine. (Courtesy of R. S. Mosher, General Electric Co.)

other work.

For a man to operate a quadruped master-slave vehicle, arm-control harnesses might have to be added, presumably with the man assuming a rather uncomfortable crawling position (perhaps in a slung harness). When the number of legs exceeds four (say, a hexaped), another operator working in concert with the first would be required. It might be easy for them to walk in a synchronized gait on level ground, but considerable training

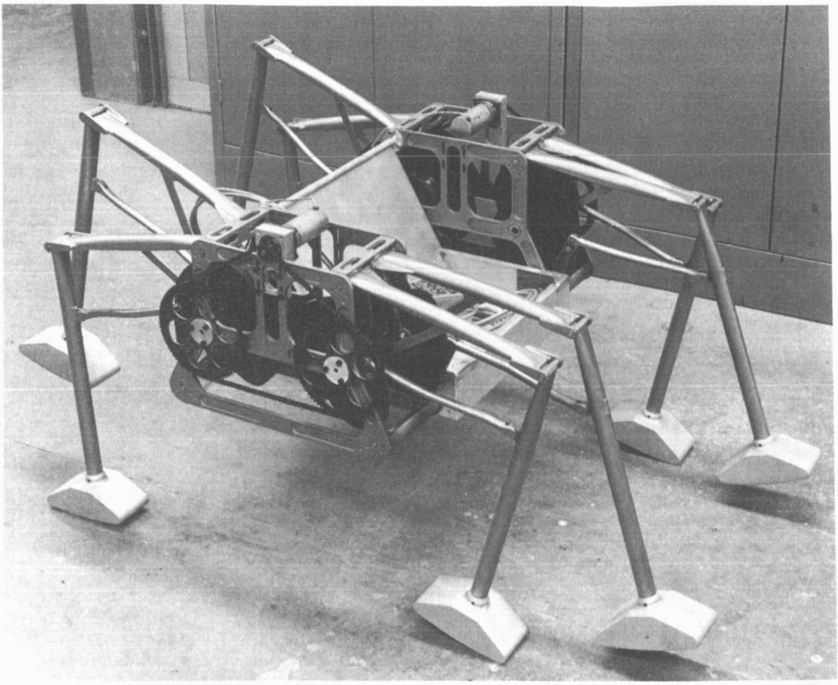

FIGURE 103.—The Space-General walking machine with side panels removed to show the motor-driven actuating mechanisms. (Courtesy of R. A. Morrison, Space-General Corp.)

would be needed to enable a machine with two or more operators to traverse rough terrain. To relieve the problem of coordinating operators, some of the legs might be programmed to follow the actions of the operator-controlled legs, making the proper allowances for gait and the terrain encountered by the lead pair of legs.

Several automatic preprogrammed walking machines have been built, notably those by Shigley (chapter 2) and Space-General.* Both of these machines had legs or frames that operated in pairs on either side of the vehicle. Neither was a true teleoperator. In the Space-General machine, fig. 103, eight legs are preprogrammed to operate as four pairs in a sequence that keeps four legs on the ground at all times for the sake of stability. These electrically actuated automatic walkers have successfully demonstrated the feasibility of walkers, but they are far from master-

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*Some simple "drag-lines" can be considered simple walking machines. See Liston and Mosher, ref. 89, for a historical discussion of walking machines.

slave-controlled walkers capable of traveling over unpredictable terrain.

ELECTRICAL TELEOPERATORS

In comparison with hydraulic actuators, electrical solenoids and motors are high-speed, low-force (or torque) devices. For high strength, they have to work through long, fallible, noisy gear trains. In comparison with mechanical teleoperators, such as the Mod-8 master-slave, electrical master-slaves are more complex, more costly, and demand considerably more engineering support for maintenance, repair, etc. The simpler unilateral electrical manipulator does not have the dexterity of the master-slaves. Notwithstanding, electrical teleoperators not only survive but multiply. The reasons are many.

An amputee likes an electrically powered prosthesis because it does not require clumsy pneumatic or hydraulic hardware draped about him. Neither are there uncomfortable straps and harnesses —only simple switches, which in the case of electromyographic (EMG) control, can be activated with the flick of a muscle.

The simplest way to pierce a barrier or overcome distance is with electrical signals. For this reason, teleoperators proposed for outer space are generally electrically actuated. Although hydraulic actuators can be made essentially leakproof, electric actuators are usually preferred in hot cells because fluids are hard to clean up from hot cell interiors and may contaminate reactor coolants, high purity atmospheres, etc.

Electrical Unilateral Manipulators

Electrical unilateral manipulators are second only to the ANL-conceived all-mechanical master-slaves in terms of total number in use. Most are employed in the nuclear industry, though several were modified for use in the early submersibles, and some industrial applications find them advantageous (see chapter 2). Whether the electrical unilateral manipulator arm is one foot or 50 feet long, it is basically a series of joints and links, with each joint driven by an electric motor. The operator usually actuates these joints with either an array of switches or a joystick without force feedback of any kind. Sometimes proximity indicators and/or force-measuring transducers are installed at the manipulator hand, but nonetheless, the man-machine relationship is not so intimate as it is in the electrical bilateral master-slaves described in the next section.

Melton has classified electrical unilateral manipulators according to their types of mountings (ref. 90):

1. Overhead bridge-crane mountings.
2. Wall mountings.
3. Overhead monorail mountings.
4. Pedestal mountings.
5. Vehicle mountings.

The overhead bridge-crane mounting, with its X-Y-Z motion

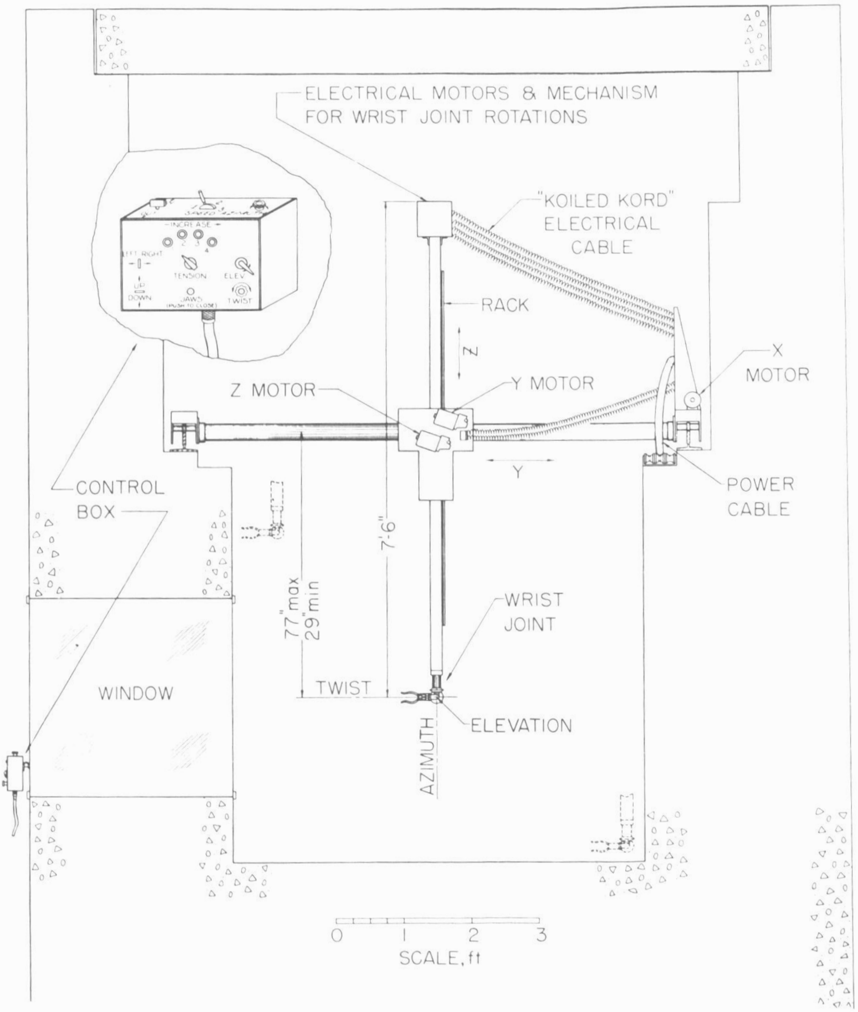

FIGURE 104.—Vertical view of an early ANL electric unilateral manipulator. Developed in 1948–1949, ANL Model 4 had a load capacity of about 4 lbs. (Courtesy of Argonne National Laboratory.)

was employed in the late 1940's and is still very common (fig. 104). It was, of course, this rectilinear type of positioning that led to the common but incorrect equivalence of the terms rectilinear and unilateral. Even in fig. 104 only the three motions that position the hand at a point in space may be called rectilinear; the rotations of the hand are best termed "polar." This type of mounting is common in hot-cell work.

Wall-mounted booms, fig. 105, are also rectilinear insofar as their motion along the wall is concerned; the rest of the degrees of freedom are polar. Wall-mounted manipulators are features of the immense hot cells associated with the various programs of the NASA-AEC Space Nuclear Propulsion Office, such as the nuclear rocket E-MAD building in Nevada.

Overhead monorails and pedestals are occasionally found in nuclear installations, but they are not abundant. A good many vehicle-mounted electrical unilateral manipulators, however, are assigned to emergency and routine operational tasks in nuclear facilities.

In configuration, most electrical unilateral manipulators resemble some of the all-hydraulic and electrohydraulic manipulators discussed earlier. The shoulder joint generally has two degrees of freedom (one pivotal and one rotational); the elbow

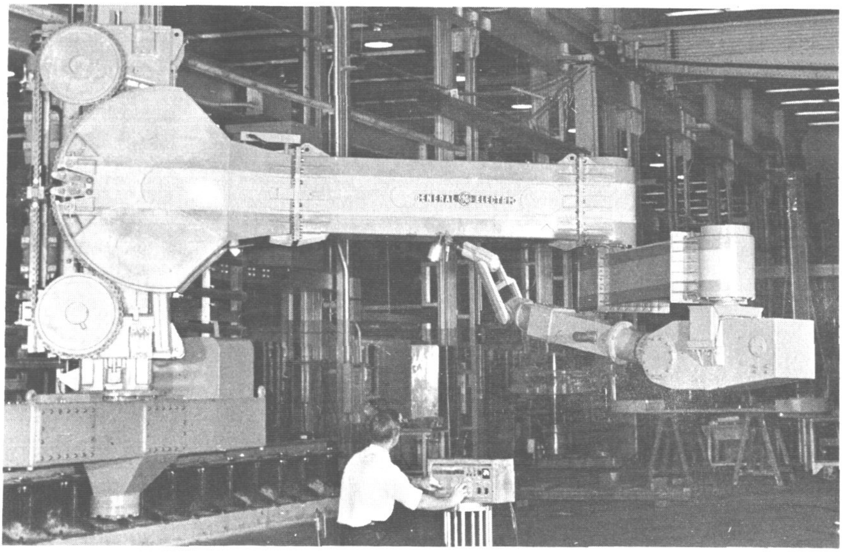

FIGURE 105.—The General Electric electric unilateral boom joints on the Wall-Mounted Handling System, at the E-MAD Building, NRDS, Nevada. Photo was taken before the concrete shielding walls were poured. (Courtesy of General Electric Co.)

joint pivots in one degree of freedom, the wrist can pivot or extend to add two more degrees of freedom, and, finally, the hand can grip and rotate, making a total of seven degrees of freedom. If the manipulator arm is mounted on a bridge-crane carriage, on a sliding column, three more degrees of freedom are added. The carriage can carry the arm over wide areas that could not be reached by the through-the-wall master-slaves seen in small hot cells. The extra mobility is purchased at the cost of the dexterity and force feedback of the mechanical master-slave. A final note on configuration: electrical unilateral manipulator arms are almost invariably mounted singly rather than in pairs—the single unit requires considerable concentration by the one operator to handle switch-box or joystick controls.*

In the usual electrical manipulator, all degrees of freedom are driven through clutches by reversible dc motors (fig. 106), each powered by a separate magnetic-amplifier system that provides stepless variable-speed control. Linear motion can easily be provided by a screw-and-nut drive. The use of mechanical slip clutches provides a measure of overload protection, which is al-

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*The great utility of force feedback in assembly, repair, and maintenance work is often glossed over. Force "feel" makes the manipulator compliant to the task (as mentioned in chapter 3) and enables two manipulator arms to work simultaneously on the same task. In contrast, two unilateral manipulator arms could not easily manipulate the same object in the absence of force feedback.

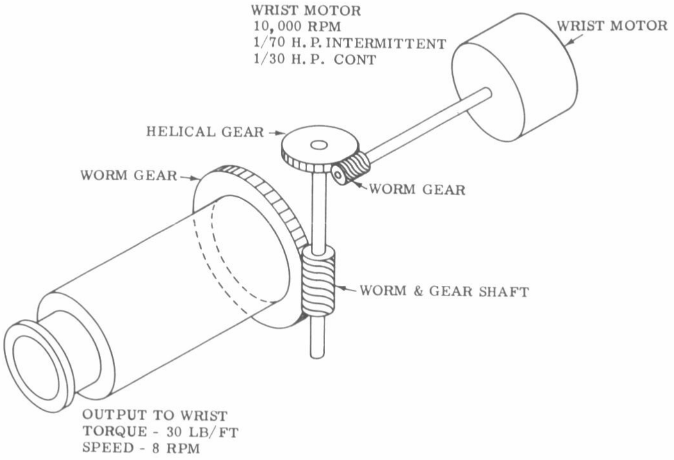
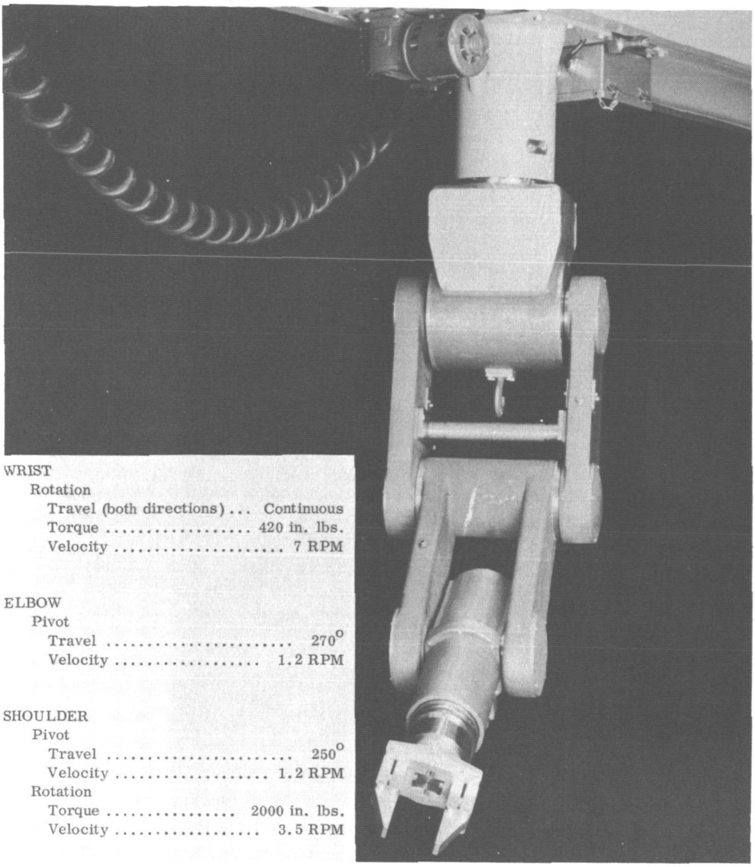


FIGURE 106.—Sketch of a typical wrist drive assembly from an electric unilateral manipulator. (Courtesy of R. Karinen, Programmed and Remote Systems.)



WRIST	
Rotation	
Travel (both directions)	Continuous
Torque	420 in. lbs.
Velocity	7 RPM
ELBOW	
Pivot	
Travel	270°
Velocity	1.2 RPM
SHOULDER	
Pivot	
Travel	250°
Velocity	1.2 RPM
Rotation	
Torque	2000 in. lbs.
Velocity	3.5 RPM

FIGURE 107.—The PaR Model 3000 electric unilateral manipulator arm. Upper and lower arm segments are each a foot long. (Courtesy of R. Karinen, Programmed and Remote Systems Corp.)

ways desirable in teleoperators where there is no force reflection. In the case of the hand gripping motion, the applied force can be controlled through an electromagnetic clutch in which the applied voltage controls the degree of coupling to the screw-and-nut drive.

Electrical unilateral manipulators are made in all sizes and load ratings. To illustrate the general configuration, the PaR (Programmed and Remote Systems) Model 3000 manipulator is shown in fig. 107.

The Los Alamos Minotaur—presumably so called because of its bull-like strength and man-like arms—is an exception to the statement that electrical unilateral manipulator arms are used

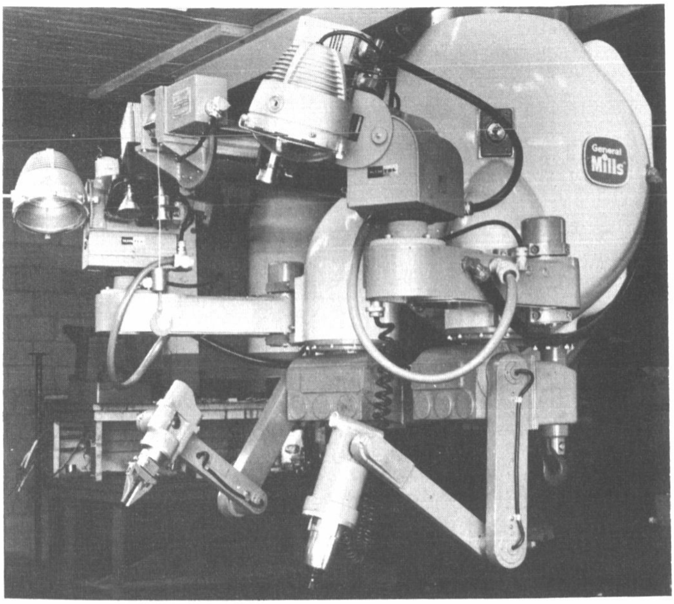


FIGURE 108.—The Los Alamos Minotaur electric unilateral manipulator system. (Courtesy of Los Alamos Scientific Laboratory.)

singly (fig. 108). A pair of manipulator arms plus a second pair of adjustable arms holding lights and TV cameras protrude from a sphere-like turret supported from above by a bridge-crane carriage. The Minotaur was originally built to Los Alamos specification by General Mills, Inc. A representative application is the maintenance of radioactive equipment in the shielded bay containing the Los Alamos UHTREX (Ultra High Temperature Reactor Experiment) (ref. 91).

The Minotaur now incorporates PaR Model 3500 with a capacity of 50 pounds in any configuration. The hand grip is adjustable between 0 and 75 pounds. Minotaur's overhead access to the working area by means of a telescoping support tube and the bridge-crane carriage is almost mandatory in the UHTREX application because the working area is a maze of large and small components, pipes, and many electrical conduits. Without an overhead mobile teleoperator with TV cameras, much of the work space would be inaccessible for months.

A rather unusual electrical unilateral teleoperator is the Serpentuator (Serpentine Actuator) under development at Marshall Space Flight Center (fig. 109). The Serpentuator consists of links several feet long separated by joints driven by electric motors,

FIGURE 109.—Five links of a prototype Serpentuator. Eighteen of these links would make an "arm" 60 ft long, with a tip force of 3 lbs in any direction in a zero g environment. The Serpentuator provides astronauts with a long, controllable arm to help them in extravehicular activities. (Courtesy of H. Wuenscher, MSFC.)

or, in one version, electrohydraulic actuators. With maximum deflections of about 20° per joint, the teleoperator can be coiled up in circular loops 20 feet in diameter and housed in the shroud of a Saturn rocket. Using switch controls at both ends of the Serpentuator, the operators can transfer tools, retrieve objects, aid astronauts, and perform other tasks in weightless space where positive controlled motion over distances greater than a few feet are difficult.

Electric Arms

In 1945 an inventor named Samuel Alderson interested Thomas J. Watson, Sr., then president of IBM, in applying electricity to help many amputees from World War II. For about six years, using funds provided by IBM and the Veterans Administration, some remarkable pioneering work was carried out by Alderson and his coworkers (ref. 76, fig. 110). Since then many individuals and organizations have advanced the art of electrical prosthetics and orthotics. Electric arms have benefited substantially from space research in terms of smaller batteries, smaller

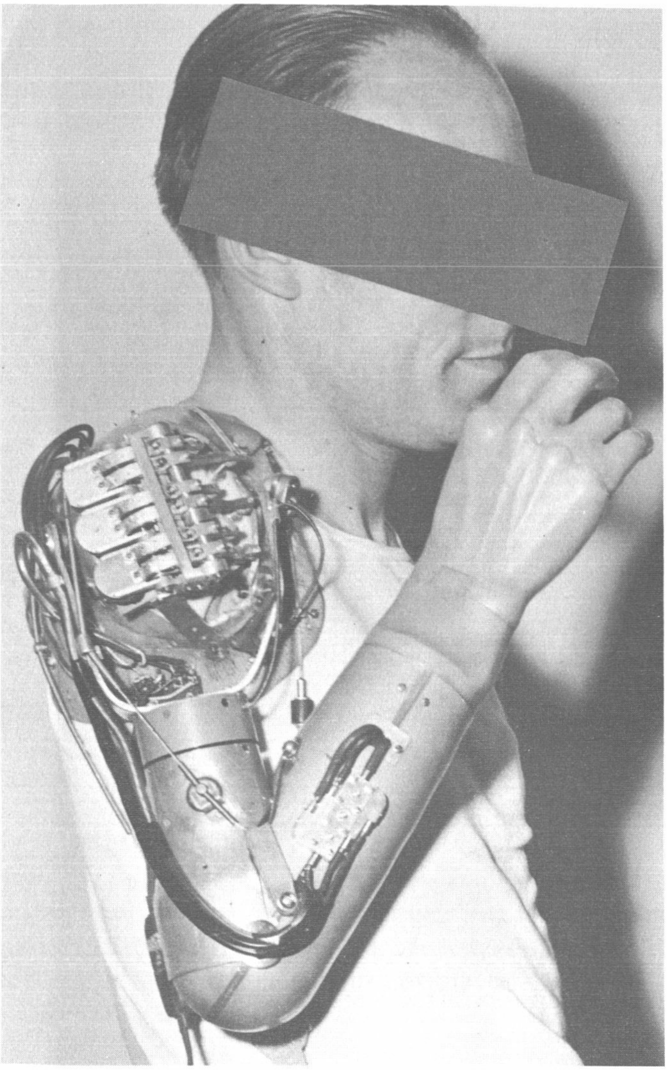


FIGURE 110.—The IBM electric arm, built circa 1950. (Courtesy of E. Murphy, U.S. Veterans Administration.)

and more efficient motors, and advanced control techniques (fig. 111). Nevertheless they have not yet come into widespread use.

The electric arm, whether for prosthetic or orthotic applications, consists of a series of rigid links connected by motor-actuated joints. In this, there is little difference between the hot-cell manipulator and the prosthesis. The electric arm, however, must be lightweight, use little power, be quiet, and be easy to

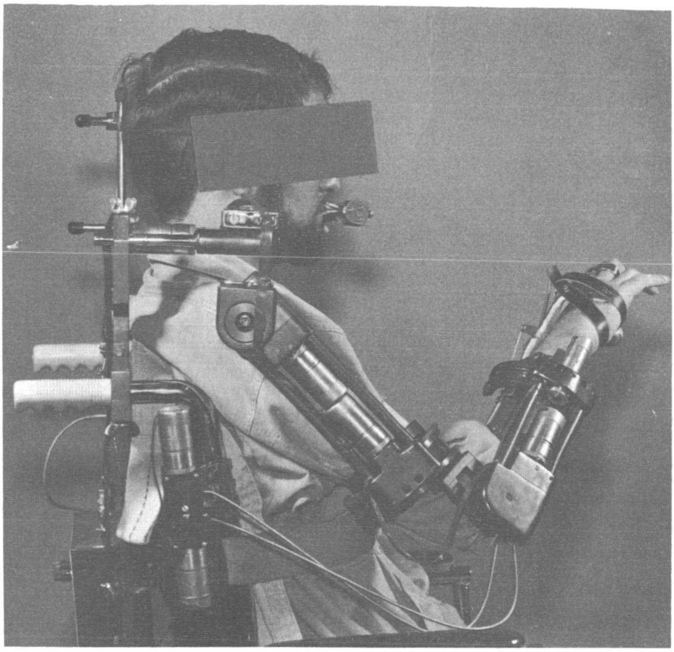


FIGURE 111.—The Rancho Los Amigos Hospital electric orthotic arm. Electric motors controlled by the tongue allow partial use of the disabled arm. (Courtesy of A. Karchak, Jr., Rancho Los Amigos Hospital.)

control even though its operator has no analogous limb. The electric motor is considerably more responsive, efficient, and flexible than an electric solenoid actuation of an artificial arm. In particular, the permanent-magnet, dc electric motor is lightweight and quiet. These motors are high speed (on the order of 10,000 rpm) and must be geared down before they can transmit power through a clutch to the joint. The clutches are usually of the multiple-disk friction type so that the force transmitted can be made proportional to the command signal generated by the amputee through a control cable. When the desired position has been attained, the joint must automatically lock itself.

Since two-way joint action is required and the amputee's signaling muscle usually produces only a unidirection signal, the control logic must be such that a series of shoulder shrugs, for example, will be properly interpreted as go, stop, and reverse signals. Since control-signal sites are very limited in the vicinity of an amputation, the controllable degrees of freedom of an electric arm are few in number. It is possible, of course, to use other body sites and electromyographic electrodes for more sophisticated control signals. After all, the amputee would like to have an arm approaching the versatility of the normal human arm. In the IBM project, three pressure switches were installed in a pad worn in the shoe. The big toe, little toe, and heel could close these switches in various combinations to actuate various degrees of freedom. While the proper switch sequences were easily learned, control of the arm required excessive concentration by the wearer. Today's electric arms usually use a few pressure switches that can be activated inconspicuously.

Most amputees prefer the simplest prosthesis they can find and many will dispense with an artificial arm altogether rather than try to cope with a maze of wires and switches. Electrical artificial limbs can certainly be made simpler because modern technology has generated miniscule, logic circuits that can relieve the amputee of many control problems, particularly if EMG signal sources are used. A form of "supervisory control" in which various EMG signals from several body sites are blended electronically could give amputees almost natural control over their artificial limbs. This technological "fallout" from computer control work may be one of the important byproducts of space research.

Electrical Master-Slaves

Mechanical master-slaves are undeniably extremely dexterous and versatile industrial manipulators. Their ability to operate through barriers and over large distances is limited by the lengths of their control cables. The bundle of control cables can be replaced by hardwire or radio links if electric servo motors are installed at both master and slave ends. Ray Goertz and his associates at Argonne National Laboratory accomplished this "electrification" of the master-slave in 1954. Without question, the ANL electrical master-slaves are superb examples of advanced teleoperator art. Only the cost and complexity of the electrical master-slave have retarded many commercial applications. In outer space and in some nuclear and undersea tasks, it is one of the best engineering solutions to the problem of projecting man's dexterity over distance and through recalcitrant barriers.

Argonne National Laboratory has built four different models of electrical master-slaves in the last decade and a half. Models E1 and E2 were developmental models. Four Model-E3 arms installed in the Chemical Engineering Senior Cave at Argonne have performed well for several years (fig. 112). The Mark E4A is presently a developmental model with such improvements over

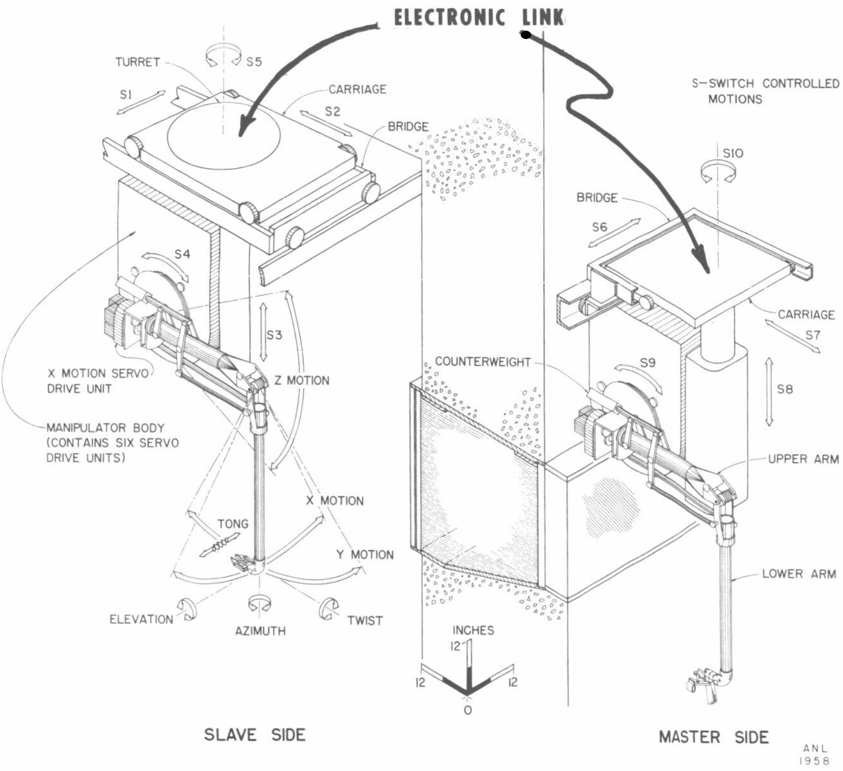


FIGURE 112.—Installation diagram of the ANL E3 electric master-slave. The normal degrees of freedom of the master-slave are combined with additional degrees of freedom provided by the overhead rectilinear bridge-crane-type carriage. (Courtesy of Argonne National Laboratory.)

Model E3 as controllable force-multiplication ratios up to 5:1, lower cost, lower maintenance requirements, lower backlash and inertia, and better working geometry (ref. 92).

The control circuits and servo arrangement for Mark E4A were described in chapter 4. The motions and degrees of freedom of the Mark E4A are essentially the same as those of the Mod-8 mechanical master-slave. Servo drives and force-reflecting servos make the E4A (fig. 113) completely bilateral (see figs. 52 through 54 and the accompanying text). Most of the degrees of freedom are driven by tapes like those employed in mechanical master-slaves. The difference, of course, is that these E4A tapes are actuated by servo drive motors located in the rather substantial "body" of the slave arm (fig. 114). The entire slave "body" and arm are free to move in space as long as a hardwire or radio link is maintained with the master. Even terrestrially such mobility

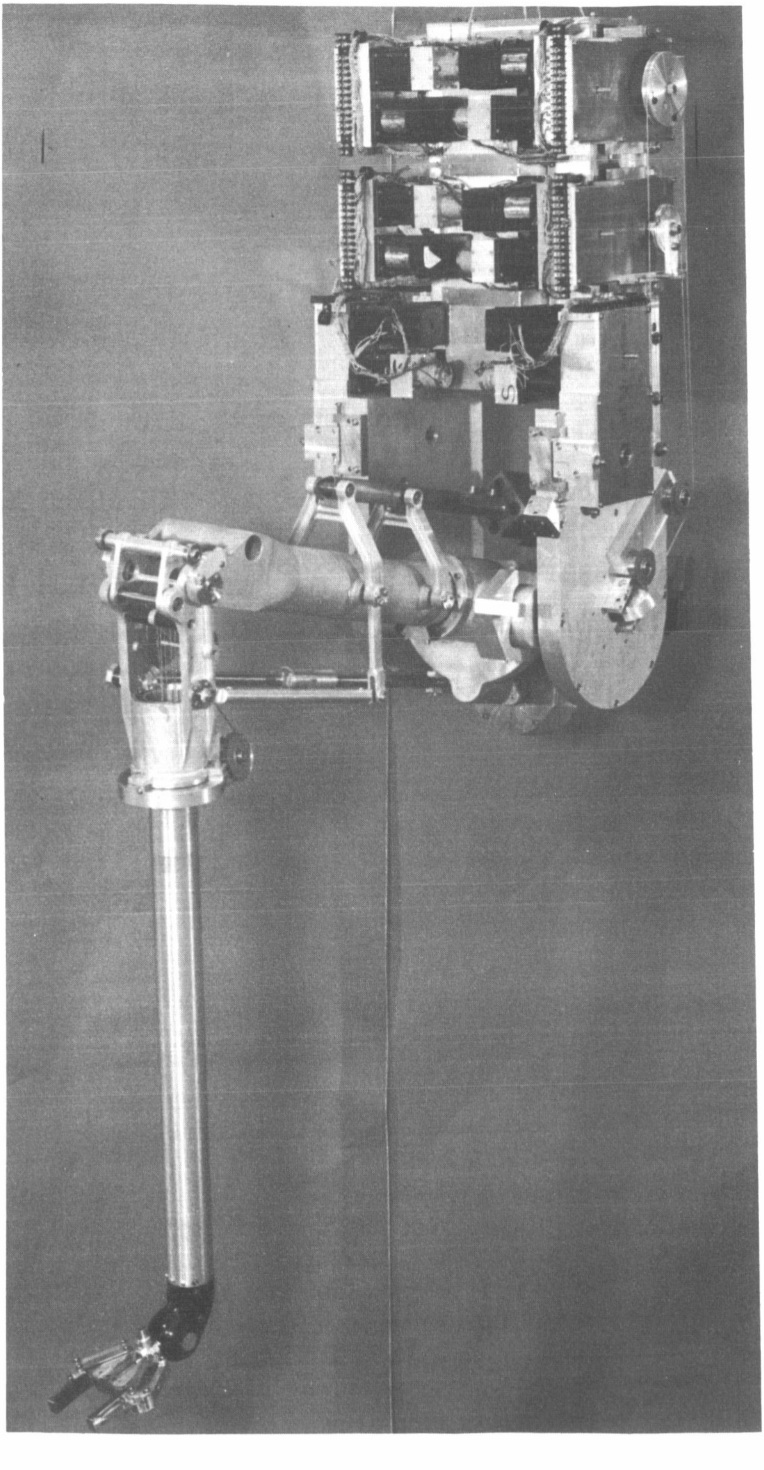


FIGURE 113.—Slave arm of the ANL Model-E4A electric master-slave. (Courtesy of Argonne National Laboratory.)

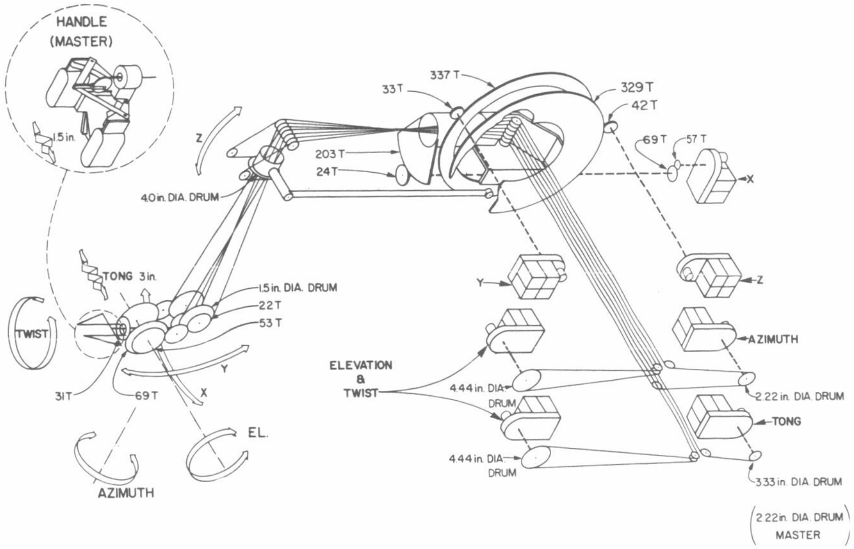


FIGURE 114.—Schematic of the cabling and servo-drive system used on the ANL E3 electric master-slave. (Courtesy of Argonne National Laboratory.)

is an advantage. The E3 hot-cell installations at Argonne, for example, use bridge-crane type carriages to move the arms over large cell volumes, something impossible with mechanical master-slaves. Here is a case where the possible motions include seven bilateral degrees of freedom and five unilateral, switch-controlled degrees of freedom.

During the MSFC Independent Manned Manipulator study (discussed in chapters 2 and 4), ANL investigated the possibilities of employing electric manipulators for the Maneuvering Work Platform (MWP) and Space Taxi concepts. Both the MWP and Space Taxi designs carried simple unilateral manipulators for docking and anchoring purposes. These arms would not be able to carry out dexterous operations in space. The Space Taxi concept also incorporated a pair of bilateral electric arms (fig. 115). Each of the slave arms had seven master-slave degrees of freedom and eight indexing motions. Four of the indexing motions were intimately associated with master-slave degrees of freedom; they were used to expand the working volume accessible to the cramped master controls in the space capsule. When the envelope of the operator's control volume was reached, the slave arms were automatically repositioned. The other four indexing motions were switch-controlled and were employed grossly to reposi-

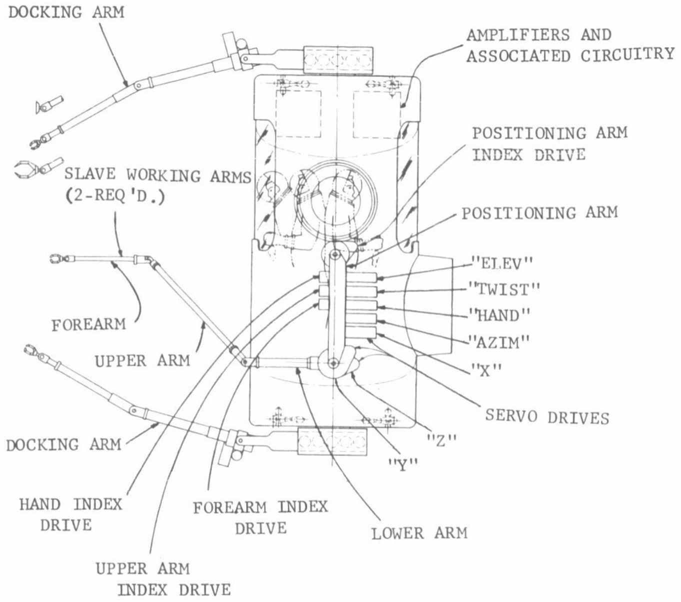


FIGURE 115.—The MSFC-ANL Space Taxi electric master-slave manipulator arrangement. There are two master-slave working arms and three docking arms.

tion or "reshape" the slave-arm configurations. The Space Taxi manipulators employed the same servo and control techniques discussed in connection with the ANL E3 and E4A electric master-slaves.

The indexing techniques used in the Space Taxi concept are applied to all types of manipulators. One would expect that indexing would make master-slave operations difficult because it destroys spatial correspondence, but this factor becomes important only when the indexed angles exceed about 30°. In space and undersea applications, where manipulator control volumes are very restricted, indexing or some form of replica control must be adopted to gain reasonable working volume.

ADVANCED ACTUATOR CONCEPTS

Electrical and hydraulic motors and pistons are convenient enough for most industrial and hostile-environment applications, but they are heavy, awkward, power-consuming, and often noisy. The deficiencies of conventional actuators have led to several studies of "artificial muscles."

Most of these investigators have tried to obtain linear force and motion through the surface distortion of flexible tube-like structures using gas pressure. The McKibben muscle, for example, consists of a straight braided sleeve and a gas-tight inner tube (fig. 84). When valves admit a gas or liquid, the cylinder bulges and the two ends are pulled together (ref. 93). Other investigators have employed fiber glass tension fibers in an elastomer tube to achieve the same effect (ref. 94). Still another variation is the spherical-cell muscle studied by Reswick (ref. 95). In this artificial muscle a rubber and cloth tube was constricted by bands at intervals along its length—looking something like a string of link sausages. When gas pressure is applied, each link or "cell" distorts and becomes more spherical. The overall effect is contraction, just as if a series of McKibben muscles were connected in series.

A slightly different tack was taken by B. F. Goodrich in a "rubber muscle" project. If a straight piece of rubber hose with specially wound reinforcing cord is pressurized with a liquid or gas it will bend to form an arc; if more pressure is applied, the curvature increases until the hose becomes a ring. Goodrich made a six-finger "hand" from this special hose that had some prehensile properties (fig. 116).

One wonders whether magnetic and electrostatic forces might not be employed to construct muscles more sophisticated than those made from deforming surfaces. The phenomena of magnetostriction and electrostriction do not provide enough contraction per unit length to serve as actuators. Electrostatic forces can be harnessed in principle to provide contraction, but the problems connected with the generation and safe handling of high voltages are very imposing, particularly in prosthetics and hostile environments. In fact, it is electromagnetic machinery rather than electrostatic machinery that dominates electric power technology. It is not surprising, then, to find electric muscles based on electromagnetic rather than electrostatic forces.

Rubber magnets frequently are used in refrigerator door latches, magnetic zippers, and the like. The core materials consist of rubber impregnated with magnetic particles. These are permanent magnets. By winding a coil solenoid-fashion about a dispersion of magnetic particles dispersed in soft rubber, the particles, which are tiny magnets, can be forced to attract one another and thus cause the rubber to contract. To provide a complete magnetic circuit, a magnetic muscle "cell" might be built in toroidal form, as shown in fig. 117. A current in the toroid windings creates a contractive force. Giannini Controls Corp. has constructed working models of magnetic muscles.

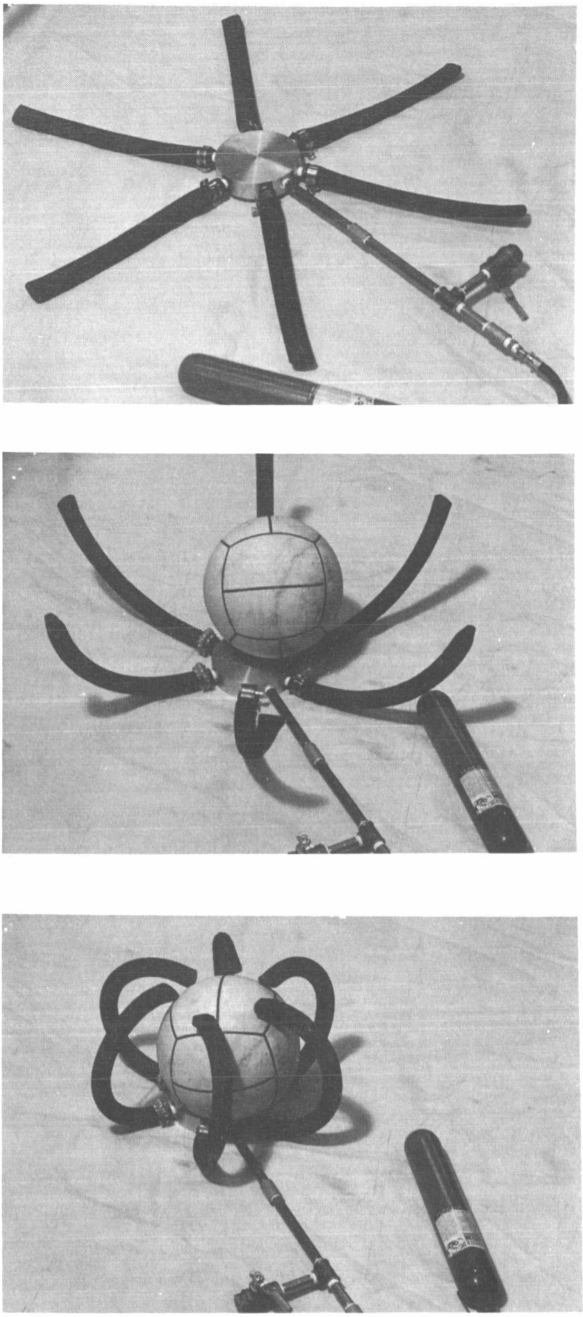
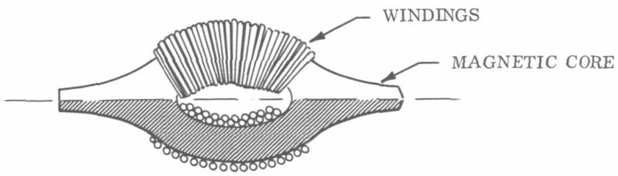
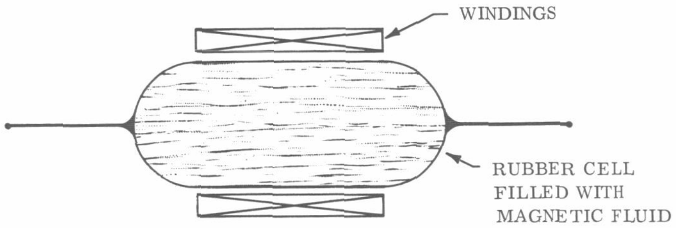


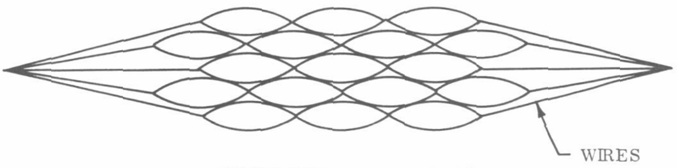
FIGURE 116.—The Goodrich "rubber muscle," shown in various degrees of "contraction." Higher gas pressures cause the muscle to deform more nearly into a circle. (Courtesy of B. F. Goodrich.)



TOROIDAL MAGNETIC MUSCLE CELL



MAGNETIC MUSCLE CELL
USING MAGNETIC FLUIDS



MAGNETIC MUSCLE CELL
ARRAY FORMING
COMPLETE MUSCLE

FIGURE 117.—Some sundry ideas for magnetic muscles. (Courtesy of Giannini Controls Corp.)

Going one step further, the impregnated rubber of the magnetic muscle may be replaced by a magnetic fluid, such as magnetic particles suspended in kerosene (ref. 96). Although still in the research-and-development stage, the magnetic muscle holds some promise for handicapped persons.

CHAPTER 6

The Sensor Subsystem

Teleoperator sensors vary as much as the arms and hands we have described—perhaps more so, because man's sensors are more diverse and subtle than his extremities. At one sensory extreme, direct vision is augmented by a crude sense of touch conveyed through the handles of simple manipulator tongs; at the other, robots far from Earth may be controlled by an operator surrounded by banks of blinking electronic consoles and displays that convey to him the sight, sound, and feel of the alien environment (fig. 118). In teleoperator terminology, the operator wants to "project his presence" into a hostile environment or across distance. The function of the sensor subsystem is to reproduce faithfully those physical properties of the working space that the operator needs to do his job well. It does not mean duplicating *all* the color and thermal nuances of the environment—just enough sensations to carry out the required manipulations expeditiously. Even with this narrowing of the sensory spectrum, the engineering task is difficult.

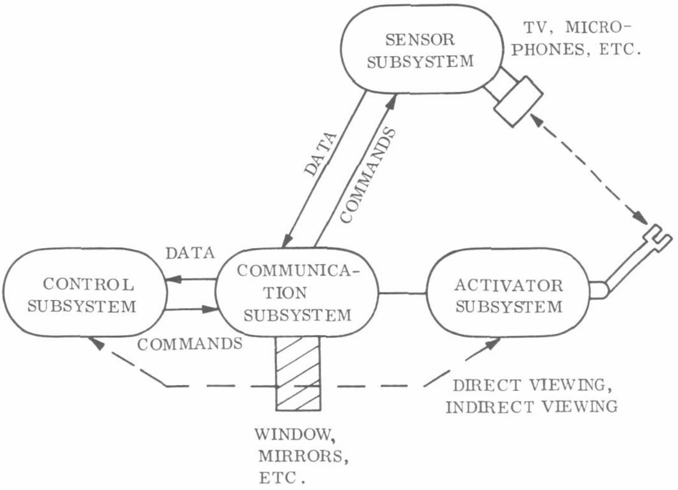


FIGURE 118.—Block diagram of the subsystems involved in providing the operator with sensory information.

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Although this chapter deals with only three of the five categories of sensory feedback an operator may receive from the communication subsystem, all five categories of sensors are listed below:

1. *Vehicle navigation sensors.* This category includes gyros, LORAN, startrackers, direct vision, radars, and the myriad of navigation aids developed to pinpoint something (the teleoperator) in space, on land, or under the sea.
2. *Target tracking sensors.* Here, we include human eyes, TV, imaging sonars, radars, proximity devices, touch sensors, force feedback, and all sensors that tell the operator the position, velocity, and orientation of the target with respect to the arms and hands of the teleoperator.
3. *Target intrinsic-property sensors.* This rather unusual class of sensors conveys information about the weight, texture, hardness, temperature, radiation level, and other target properties that are independent of those sensed in Category 2.
4. *Teleoperator status sensors.* These sensors relay data about the health of the teleoperator, such as internal temperatures and summaries of switch positions. Also included are critical data telling the operator the positions, velocities, and accelerations of all degrees of freedom in the actuator subsystem. Commonly, the operator's eye receives such information directly or by TV. If the operator cannot see the scene, transducers on the manipulator joints may relay vital information.
5. *Environment sensors.* Teleoperators are more effective if the operators know something about the environment in which the target and manipulators are immersed. Microphones, thermometers, radiation detectors, ocean-current meters, and a wide spectrum of other "environment" instruments have been developed during nuclear, space, and underseas programs.

Most sensor possibilities in Categories 1 and 5 are already well treated in the aerospace, nuclear, and underseas literature. We shall concentrate upon those sensors that augment the operator's visual, auditory, and tactile senses, with only brief forays into more advanced concepts.

Table 18 (ref. 97) shows that men have more senses than the classical five, but manipulation is done mainly by sight and feel. The first task of the designer is partially to reproduce these two factors within the given cost and engineering constraints.

TABLE 18.—*Human Senses of Actual and Potential Interest.*

Sensor category	Sense	Utility in teleoperators
Photoreceptors	Sight	Estimates distances, velocities, color, texture, orientation, etc.
Mechanoreceptors	Feel	Estimates weight, pressure, vibration, wind speed, impact, slippage, texture, size, etc.
	Hearing	Detects sliding, mechanical strains, motion, liquid flow, relay action, breakage, etc.
Chemoreceptors	Smell	Estimates composition, chemical reactions (fires), etc.
	Taste	Estimates chemical composition.
Thermoreceptors	Heat	Estimates temperature crudely, locates heat sources.
Electromagnetic receptors		None known for man, though some fishes and (perhaps) birds use such senses.
Balance	Balance	Determines gravitational stability or the lack of it.

Auditory and visual alarms cues are useful, as subsequent sections will show, but without question, major attention must be directed toward translating the physical situation in the working space into those sensory terms that the operator employs in eating, writing, and playing dominoes. Even nonanthropomorphic sensors, such as imaging sonars and precision radars, should render their information visually for human comprehension. In other words, the sensory picture should resemble scenes in ordinary life.

Each environment has its own sensory problems. Some are generic, such as adequate target illumination (light, sound, radar) and visual obstructions of the target by barriers and the manipulators themselves. Others, such as light scattered by the sediments stirred up around a distressed submarine, are highly specific. Some other specific problems are listed in table 19 along with some typical solutions.

DIRECT-VISION SITUATIONS

Most of the teleoperators now in use let their human operators see the targets, the manipulators, and their spatial relationships directly. Every possible effort is made to improve the clarity, realism, and field of view available to the operator, because the

TABLE 19.—*Some Sensory Problems by Application Area.*

Application area	Specific problems	Some solutions
Aerospace	Limited communication bandwidth	Data compression, supervisory control
	Micrometeoroid damage to optics	Removable lens covers
	Ultraviolet browning of optics	Filters, special glasses
	Degradation of sensors during heat sterilization	Special heat-resistant electronics and sensors
	Vacuum welding	Special lubricants and materials
Undersea	Scattering of light by suspended particulate matter	Use long wavelengths and proper angle between light source and sensor Imaging sonar
	Corrosion, fouling	Paints, coatings, remote cleaning devices, proper materials choice
Nuclear	Radiation damage to optics, electronics, and many sensors	Shields (perhaps movable), selection of radiation-resistant parts
Metal processing	Thermal degradation	Thermal shields, heat-resistant parts
Construction and mining	Explosion (shock degradation of sensors)	Shock absorbers, rugged construction
Public services	Thermal degradation (fires)	Thermal shields, heat-resistant parts
Entertainment	Concealment	Miniaturization of sensors, camouflage

eye represents the largest sensory input channel to the brain.

Direct viewing of the working space requires: (1) good lighting and (2) a good window or light path that lets the operator see without strain the light reflected from the targets and manipulator arms and hands. Lighting and light paths are not independent design problems. The intensity of light reaching the eyes of the operator depends upon both the intensity of the light source and the attenuation suffered in the window or other transmission media. Other design ingredients of somewhat lesser importance are distance, contrast, coloration, and arrangement of the targets with respect to the teleoperator hands and arms.

Lighting in outer space is notoriously variable, particularly on an Earth-orbiting, spinning spacecraft. In Earth orbit, any combination of the following situations may occur (ref. 98):

Solar illuminance	13,500 ft-candles (lumens/ft^2)
Earthshine illuminance	4500–9000
Lunar illuminance	0.03
Starshine illuminance	0.0001

Direct sunlight can render the target much too bright, and require an astronaut to use his helmet's sunshade. If work is shadowed so that neither the Sun nor Earth illuminate it, the astronaut may not see it at all because his eyes will be adapted to the bright areas surrounding the work. Obviously, supplementary illumination that can be varied at will by the astronaut is needed (ref. 99).

Human-factors engineers generally recommend an illumination of about 3 ft-candles for fine work. To attain something close to this value, an astronaut may switch floodlights on when the work rotates into deep shadows and pull down his sunshade when the work is lit by direct sunlight. Intense contrasts can be softened by requiring spacecraft parts in peripheral areas to have light-absorbing, glossless surfaces. By deployment of nonspecular reflectors at strategic spots, some of the surplus sunlight and Earthshine can be reflected into dark regions.

Far under the sea, there may be no light save that provided by the vehicle itself, but the sea is almost as fickle as outer space in its perturbations of man's activities. For example, the attenuation length for 465-mμ light, five fathoms deep in the Atlantic off Gibraltar, is about 20 yards; off the Galapagos, the attenuation length is only about one-fifth this value. To add to the difficulties on the ocean floor, enough sediment may be stirred up by a submersible to make seeing considerably worse. Variable floodlights are needed.

Several concerns manufacture underwater lighting equipment (ref. 100). Edgerton, Germeshausen, and Grier, for example, makes a series of quartz-iodine incandescent lamps, within quartz envelopes, that can be operated at depths down to 39,000 feet. Mercury-vapor lamps are useful, since their light is emitted in that portion of the spectrum where seawater attenuates light the least. Small manipulator-carrying submersibles mount several such lights at various points around the hull. A major problem with undersea (and space) lighting is the high power consumption of the lamps.

In hot cells and most other terrestrial applications there is no power-supply problem because power lines go nearly everywhere. Hot-cell interiors are usually decorated with a glossless (flat) paint that reflects light into all nooks and crannies, providing manipulator operators with almost ideal lighting conditions. The only major attentuator of light is the hot-cell window.

The viewing window of the hot cell, spacecraft, or submersible is an integral part of the communication subsystem. The overwhelming bulk of feedback information travels this route. Distortion, aberrations, and restrictions to the operator's vision must be eliminated as far as funding and technology permit. The main concern in space and undersea work is the integrity of the window in the vacuum of space on one hand and the crushing pressure of seawater on the other. Conditions are quite different

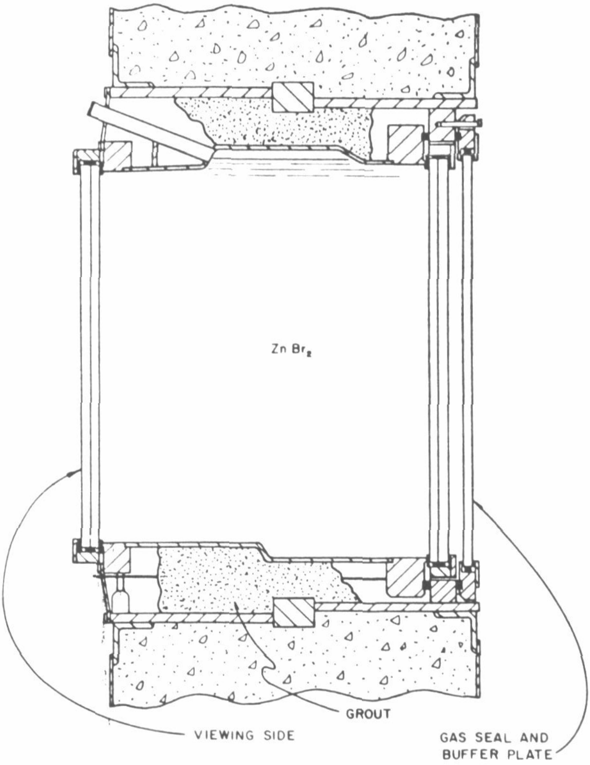

FIGURE 119.—A typical zinc-bromide hot-cell window. (Courtesy of Argonne National Laboratory.)

in the nuclear field, where the hot-cell window must allow a man to see through a very thick biological radiation shield.

Periscopes and systems of mirrors gave early manipulator operators an over-the-wall peek at what was transpiring in hot cells. But these were tiring to use. In the late 1940's, Oak Ridge National Laboratory installed some small circular cylinders filled with transparent zinc bromide (specific gravity, 2.5) in the walls of hot cells. The zinc bromide attenuated the gamma radiation and still gave the operator a direct look at his work. Unhappily, these early windows were expensive and their transparency deteriorated under large doses of radiation. The operator also had the feeling of "tunnel vision" with the small apertures.

Subsequent chemical research showed that the zinc bromide filling the windows could be stabilized in a radiation field by the addition of a reducing agent, hydroxylamine hydrochloride, in a concentration of about 0.01 percent. Windows were next widened to give the operator a better view of the hot-cell interior. Today, window apertures up to five feet square are feasible. Such dimensions give the viewer a field of view approaching 180° (fig. 119). Though liquid-filled windows may be as thick as five feet, the manipulator operator can project his "presence" readily into a well-lit hot-cell interior. The scene usually has a greenish cast (because of the window glass rather than the zinc bromide), but it is quite vivid. Sodium-vapor lamps, which emit nearly monochromatic light, prevent color fringes around objects in the cell. Distortion, which makes plane surfaces appear curved, becomes noticeable only when the viewing distance approximates the window thickness or when the viewing angle of incidence is greater than roughly 60° (ref. 101).

Water has occasionally been used instead of zinc bromide to fill liquid windows, but its lower density makes it a much poorer radiation shield. Other dense liquids that have been tried include lead acetate, zinc chloride, and methylene bromide. With further development, some such fluids may approach the effectiveness of zinc bromide. Until this happens, zinc bromide dominates the field.

Some solid glasses are considerably denser than zinc bromide (table 20). Why not substitute solid glass plates for the fluid zinc bromide? The glasses available during the early atomic energy work were unstable in the presence of gamma radiation; they discolored or lost their transparencies quickly. The addition of cerium and other chemicals to the melt improved the situation markedly. As a result, one now finds some hot-cell windows constructed from several thick slabs of glass, as illustrated in fig.

TABLE 20.—*Physical Properties of Transparent Shielding Materials*[i].

Type of glass	Density	Index of Refraction	Optical Transmittance[a]		Color	Radiation Stability Index[c]	Fading Index[d]
			Tungsten[b]	Sodium			
Commercial lime[e]	2.52	1.52	94.6	94.3	Green	2.6x10^2	2–5
Water-white lime[e]	2.52	1.52	99.0	99.0	Colorless	2.6x10^2	2–5
Nonbrowning lime[e]	2.68	1.53	96.8	97.0	Light Yellow	1.6x10^6	1–3
Corning 8362	3.27	1.59	97.6	98.2	Yellow	0.8x10^6	1–3
X-ray lead[e f]	4.88	1.76	90.0	92.0	Deep Yellow	2.0x10^2	2–5
Dense lead[g]	6.20	1.98	94.1	95.2	Yellow-orange	1.5x10^2	10–50
Zinc bromide solution[h]	2.52	1.56	98.5	99.0	Colorless	. . . .	. . . .

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[a] Optical transmittance in percent for 1-in. thickness and average specimens, less surface reflection.

[b] Light of the quality of I.C.I. Illuminant A.

[c] The exposure in r required to produce a change in optical density of 0.01 for white light and a thickness of one HVL. Optical density is the logarithm of the reciprocal of the transmittance. The exposure rate was 100 and 700 r/min.

[d] The ratio by which the exposure in (c) must be increased in order that the change in optical density is 0.01, 2 weeks after the termination of the exposure.

[e] Commercial samples from the Pittsburgh Plate Glass Company.

[f] Transmittance for laminated sections.

[g] Commercial samples from the Penberthy Instrument Company. A similar glass has been prepared experimentally by the Corning Glass Works.

[h] Commercial samples from Dow Chemical Company.

[i] Adapted from ref. 101.

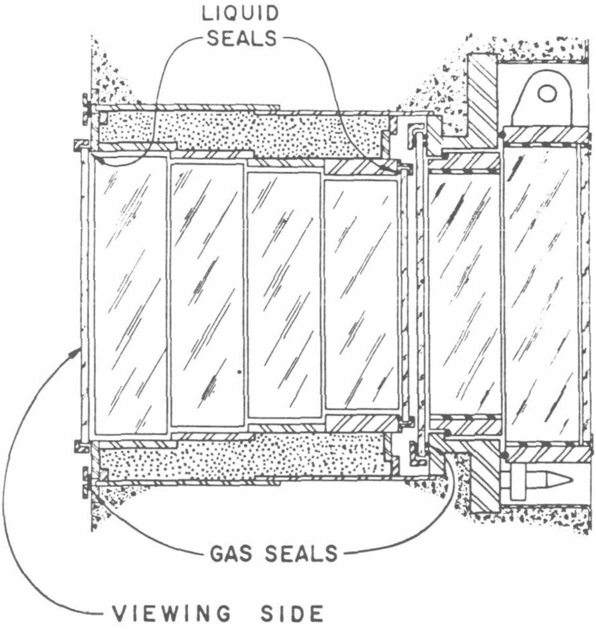

FIGURE 120.—Sketch of the all-glass window installed in the Experimental Breeder Reactor II Fuel-Cycle Facility In Idaho. (Courtesy of Argonne National Laboratory.)

120. The spaces between the glass slabs are generally filled with mineral oil because its optical properties are similar to those of the glasses.

To give the operator a greater field of view, yet keep hot-cell wall penetrations down to reasonable sizes, the windows are frequently flared or stepped; that is, they open up toward the inside of the hot cell, just the reverse of a safe door.

Pressure takes the place of gamma radiation in fixing the sizes and compositions of submersible viewports. The deeper the submersible goes, the smaller and thicker its viewports. The North American *Beaver*, for instance, is designed for continental-shelf operation where pressures are not extreme. The *Beaver*, therefore, can afford a large panoramic, plastic window (fig. 15). In contrast, the deep submersible, *Alvin I*, designed for 6000 feet, can tolerate only small hull penetrations. Its plexiglass windows are 3.5 inches thick and 5 inches in diameter on the operator's side. The *Alvin I* windows open up conically at a 45° angle (ref. 102). With this face close to an *Alvin* viewport, a manipulator operator would have a fairly large field of view, but there would be little room left for manipulator controls unless they were the small replica types (mentioned in chapters 3 and 4) or switches.

In designing a viewing system, the engineer encounters several

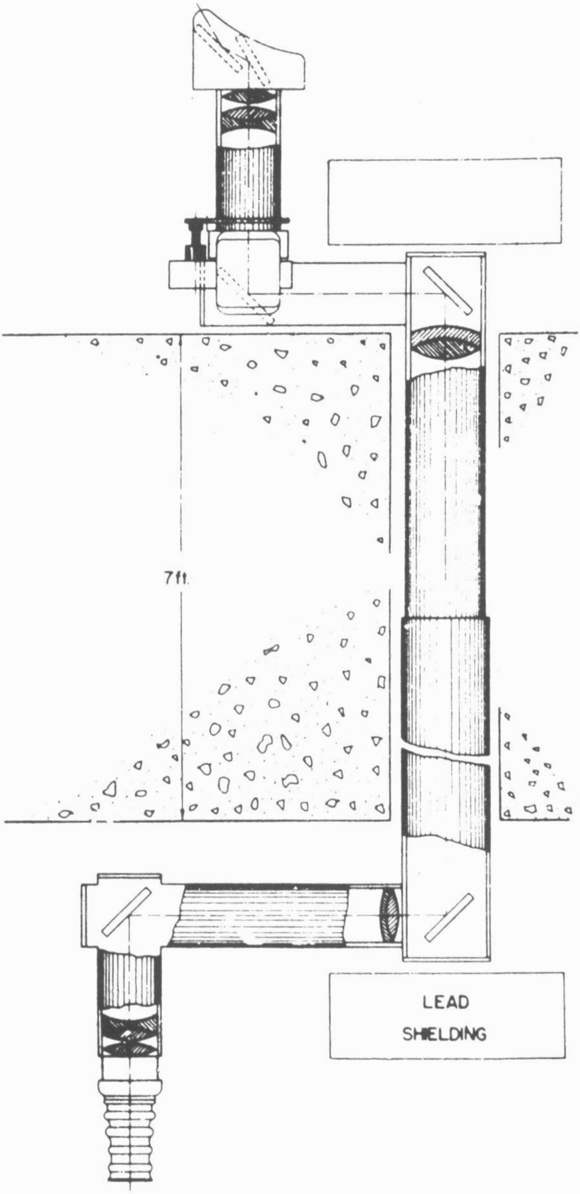

FIGURE 121.—A "corner periscope" installed in a hot-cell wall. Note that the hot-cell wall penetration is shielded at both ends.

human-factors problems. The intensity of illumination and the spacing of floodlights certainly falls into this category. Assuming good lighting, where should the work be placed relative to the operator (or vice versa, if one has no control over the work)? Should the work be color-coded? Will matching the work and the viewing system to the human operator improve overall teleoperator performance?

The human factors experiments of the Air Force's Aerospace Medical Research Laboratories provide some partial answers to these questions (ref. 103). For instance, the distance from the manipulator operator's unaided eyes to the work should not be greater than about 10 ft, less if possible. As distance increases, visual resolution and depth perception drop off and task performance time rises. The Air Force studies showed significant performance deterioration between 7 and 11 feet. Most manipulator installations, whether in the nuclear or underseas fields, provide the operator with mounted binoculars or telescopes to augment his vision should distances become too great. With visual augmentation, the distance to the work may be several times the recommended 10-foot limit, as it is in cavernous hot cells, such as E-MAD.

Wright Field studies also indicate that the work should be below the operator's horizon, i.e., he should look down on it. Task performance times were best when the angle below the horizontal was between 45° and 65°.

The loss of depth perception is a major factor causing deterioration of performance with distance. Air Force tests comparing binoculars and monoculars (telescopes) indicate that distant tasks are completed faster with the stereoscopic effects provided by binoculars. But contemporary, rather primitive, 3D TV apparently offers little if any advantage over 2D TV in manipulatory tasks. The two images needed in 3D TV are difficult to keep registered, especially if the cameras have to be redirected frequently to various parts of the work. Color TV, however, *may* improve task performance if the hands and work are specially colored to improve contrast. Further development may turn 3D TV into a superior viewing subsystem.

VIEWING WITH MIRRORS AND FIBERSCOPES

Optical devices can help an operator see around a target or barrier:

1. When he cannot maneuver his vehicle or direct-viewing equipment into good positions.

2. When there are no viewports or windows in the barrier near the operator. Sometimes the radiation levels do not permit a man to work near barrier penetrations (fig. 121).

Mirrors are often placed strategically within cells so that hidden parts of the target may be seen from the window. Periscopes with their high quality optics are excellent for photography and magnified views of a target. Mirror and periscope viewing systems can be easily converted from fixed to scanning configurations by the incorporation of scanning mirrors.

Since nuclear hot cells are fixed installations, considerable latitude exists for installing indirect viewing systems. In orbit or at the site of an underwater oil well, there is little opportunity for the deployment of special mirrors and periscopes, but there is less need for indirect viewing because space vehicles and submersibles can hover in various positions around a target.

How does one inspect remotely the inside of a tube or look inside a hatch? The borescope permits the inspection of pipes inside nuclear reactors and various other sites inaccessible to direct viewing. The borescope is essentially a periscope with its own light source. It comes with ready-made extensions that can effectively transport the operator's eye as far as 50 feet down a coolant pipe. An underwater oil well casing might be searched for a lost tool similarly; when the tool was located, a manipulator could recover it. This kind of application is similar to the Atomic Energy Commission's Down-Hole Project in which TV and a manipulator are combined to locate objects at the bottoms of deep holes drilled for underground nuclear tests.

The development of fiber optics has given the teleoperator another tool for examining inaccessible spots. A flexible bundle of hairlike glass fibers not only can carry light to the desired spot but also can bring out an image of the area. These so-called Fiberscopes have been made as long as 10 feet, and without question can be made longer. The remote manipulator would have to transport the viewing head of the Fiberscope into the target area. If the head can be secured, the manipulator operator can use its images to guide his manipulations.

REMOTE TELEVISION

The practical utility of television in manipulator operations has been controversial for almost two decades. Some operators prefer TV to direct vision; others have no use for it. In some applications, nevertheless, TV is clearly superior, even mandatory:

1. In controlling a teleoperator at distances beyond the range of direct-vision optical equipment, viz., on Mars, etc.
2. In nuclear accidents when radiation precludes the close approach of men with direct-viewing devices.
3. In locations where there are obstructions to direct viewing, such as an undersea disaster area or a cluttered hot-cell floor.
4. In situations where simultaneous observations from widely separated various vantage points are required.
5. In situations when very little light is available.

Inherent in the above statements are the major TV advantages of portability, the ability to work under very poor lighting conditions, to use a wide selection of lenses (including zoom lenses), and the ability to focus remotely, change aperture, insert filters, and so on. Nevertheless, there are some drawbacks to the use of TV: cable-handling problems, very large bandwidth requirements, electronic instability, sensitivity to high radiation fields and intense light, limited resolutions, poor depth perception, complexity, and the possibility of operator disorientation because of "unnatural" spatial relationships between the TV cameras and the manipulators.

TV can boast some notable successes in teleoperators, such as the Minotaur, MOBOT, MRMU, RUM, and the manipulators in the North American SETF (SNAP Environmental Test Facility). In the last instance, manipulator operators prefer TV viewing to direct viewing through a hot-cell window (ref. 104). While TV may be more convenient than direct viewing in many operations, everyone agrees that direct vision aided by purely optical devices (periscopes, telescopes, etc.) yields the sharpest, most realistic images.

Conventional 2D, black-and-white TV gives a rather limited representation of the complex scene a manipulator operator wishes to interpret. 3D, color TV was tried in the early 1950's at the AEC's Nuclear Reactor Test Site (NRTS), in Idaho, as part of the Aircraft Nuclear Propulsion (ANP) Program (ref. 105). The ANP NRTS Hot Shop was large enough (160- by 51-feet wide) to require visual assistance for manipulator operators—an excellent opportunity to try TV experiments. The major problems encountered with 3D, color TV were: reduced light transmission, diffusion effects with the colored images, and the cumbersome camera arrangement (ref. 106). In the end, a black-and-white stereo TV system for which the operator wore polarized glasses was adopted to give some degree of depth perception to distant scenes.

In restrospect, the ANP experiment was premature and an unnecessary setback for TV. Because of early equipment difficulties with 3D, color TV, even 2D, black-and-white TV fell into disfavor. Many years have passed since the ANP experiment; advances in the TV art would insure that the experiment would be more successful if tried today.

Recent refinements of TV have hardly been exploited at all. Only 0.5 percent of the human eye's retina is utilized by conventional TV. Too little research has been done to couple man to TV in a more comfortable and successful symbiosis.

Most teleoperator TV installations are custom-built. Nevertheless, there is a decided advantage in using commercial TV standards that specify the number of lines, number of frames per second, and so on. A large array of highly reliable commercial TV equipment has been developed. Many miniaturized cameras are available, and important accessories, such as remote pan-and-tilt units, are readily adaptable to teleoperator work.

Two major types of TV cameras exist: the image orthicon and the vidicon. The latter is lighter, cheaper, more stable, more rugged, and has longer life. The image orthicon, though, possesses greater sensitivity and resolution. For space and undersea applications, where weight and ruggedness are critical, the vidicon is the favorite choice. Vidicons have "snapped" spectacular pictures of Mars and the Moon. Other vidicons have been adapted to underseas work (ref. 100). Oceanographic Engineering Corp., for example, makes a vidicon camera that can be rated for a depth of 40,000 feet. This particular camera is built around a Type 7282A vidicon with a peak sensitivity of 450 mμ, a wavelength at which seawater is very transparent. An automatic light compensation ratio of 10,000:1 is also provided.

In outer space, the first teleoperator applications are likely to be on orbital vehicles, such as the Space Taxi mentioned previously. Such vehicles, however, will rely mainly on windows and direct viewing. Essentially the same situation exists in the sea; the small submersibles, which have missions so similar to those of their space counterparts, are provided with adequate viewports in the neighborhood of the manipulator arms. The only major underseas teleoperators employing TV as the primary sensors are the Hughes Tool Company's MOBOT and UNUMO (fig. 19), both built for offshore oil-field operations.

The TV installations on the Minotaurs at Los Alamos and Brookhaven National Laboratories are typical of many remote viewing setups where the manipulator arms and hands are so far from the human operator that direct unaided viewing is impossible. In the Los Alamos UHTREX application (see chap. 5) optical equipment, such as periscopes and telescopes, would be of little avail in penetrating the depths of the equipment-cluttered reactor bay. The Los Alamos Minotaur thus carries three TV cameras. Two are Kintel cameras with remotely controlled three-lens turrets (ref. 107). Each is mounted on a standard pan-and-tilt mechanism which in turn is fixed to pivoting booms attached to the sides of Minotaur (fig. 122). The camera turrets contain radiation-resistant lenses with diameters of 1/2, 1, and 3 inches and minimum focal distances of 12, 16, and 40 inches, respectively. The third camera, provided with a Zoomar lens, is also mounted on a pan-and-tilt mechanism, and is attached to the overhead bridge crane to give the operator an overall view of the work area. The operator console (fig. 122) has two 8-inch and one 14-inch TV monitors.

The TV installation at the North American SNAP Experimental Test Facility (SETF), Canoga Park, Calif., differs from the Minotaur in that the cameras are completely independent of the manipulators. Called "traverse" cameras, they are mounted

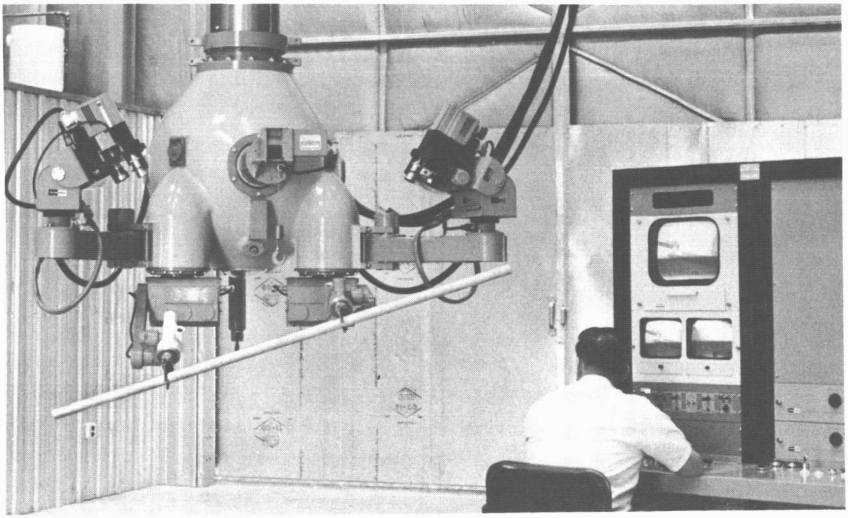

FIGURE 122.—The Minotaur electric unilateral manipulator, showing the two boom-mounted TV cameras and the operator's console. (Courtesy of Los Alamos Scientific Laboratory.)

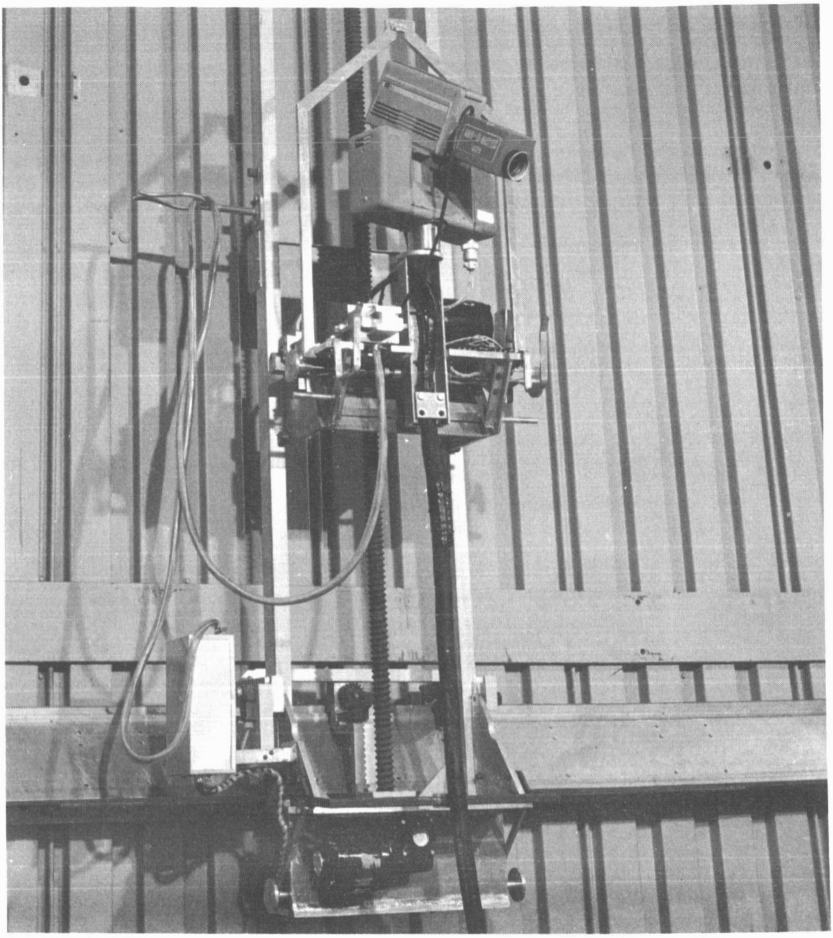

FIGURE 123.—One of the SETF "traverse" TV cameras. (Courtesy of Atomics International Division, North American Aviation, Inc.)

on dollies that run on horizontal tracks attached to the hot-cell walls (fig. 123). The manipulator operator can position the cameras acording to the task requirements by means of a joystick control (fig. 124). Several traverse cameras are often used simultaneously to view the task from different vantage points. Each camera unit is provided with a zoom lens and a pan-and-tilt mechanism. The hot-cell manipulators (electric unilateral types) can unplug and plug-in the several camera units.

The need for TV remote viewers in the SETF arose because direct window viewing of the operating reactors in the SETF

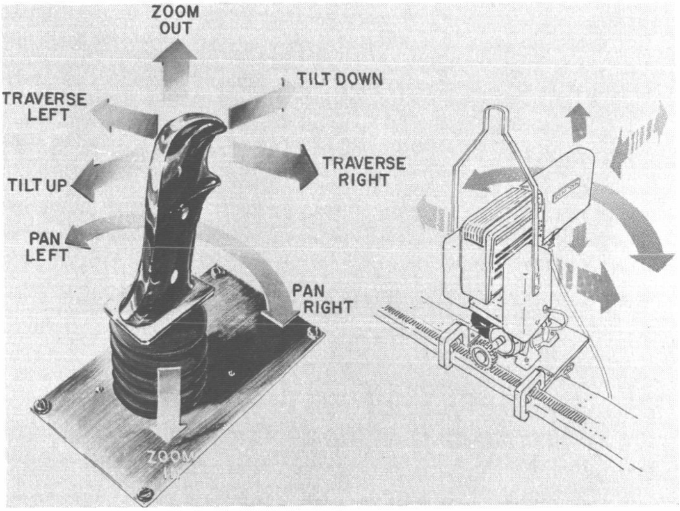

FIGURE 124.—Joystick control concept applied to the SETF "traverse" TV cameras at the SETF. (Courtesy of J. Burton, Atomics International Division, North American Aviation, Inc.)

"vaults" was deemed impossible. Windows would quickly become opaque under the intense neutron flux from the operating reactors. (Low-flux gamma rays from radioactive material do not deteriorate windows so rapidly.) The SETF vault operations were the first performed by an all-TV hot-cell teleoperator with no visual access at all. Although the center hot cell of the SETF did possess a conventional window, the manipulator operators preferred to rely on the TV.

Remotely controlled zoom lenses and pan-and-tilt mechanisms are only crude approximations to what an operator would like. It seems wasteful to distract the operator with a second joystick or another set of console switches just for camera control. What is needed is a TV camera linked or servoed to the operator's head and/or eyes just as the manipulator hands and arms are connected mechanically, hydraulically, or electrically to the operator's hands and arms. Retaining manipulator terminology, we would call this a "master-slave" television system.*

As early as 1958, Philco Corporation engineers constructed a master-slave TV headset system with two degrees of freedom—

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*In principle, optical equipment, such as scanning periscopes, could also be controlled by the operator in a master-slave fashion. Since there is no force feedback in these "master-slave" viewing systems they are actually "unilateral."

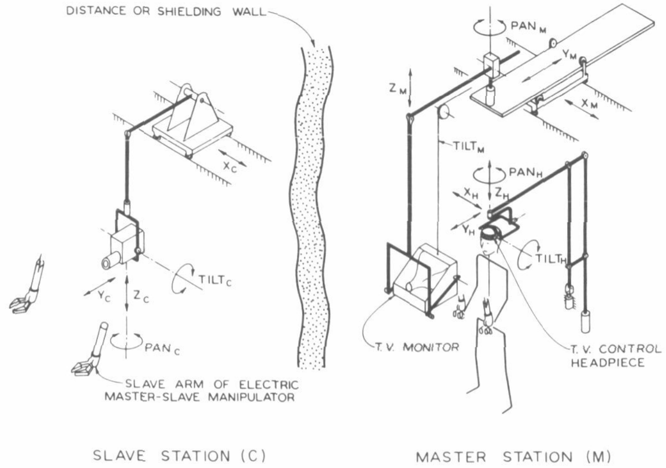

FIGURE 125.—Schematic diagram of the ANL TV2 master-slave TV control. When the operator moves his head in any of five degrees of freedom, the TV camera moves a corresponding amount (ref. 109).

pan and tilt (ref. 108). In 1965, the Argonne National Laboratory group headed by Ray Goertz produced their Mark TV1, another master-slave with two degrees of freedom (ref. 109). The success of TV1 encouraged ANL to build TV2, possessing the five degrees of freedom illustrated in fig. 125. Operating TV2 in conjunction with a pair of ANL Model E2 electric slave-master arms, an operator would bridge distance or a hot-cell barrier with a total of 5 + 7 + 7 = 19 degrees of freedom, five of them associated with vision.

The TV2 television is a General Precision, Inc., GPL Precision 800 closed-circuit system using a vidicon, commercial standards, and a Zoomar f/2 lens. Both the camera and the TV monitor viewed by the operator are servoed to the operator's head. When he turns his head to the right, the camera in the operating space turns with a one-to-one correspondence and so does the vertically suspended TV screen in front of him. The whole effect is remarkably realistic. Even more realism might be achieved if a miniature TV tube were mounted directly in the operator's helmet or if a wide-screen panorama were presented.

The human head has six degrees of freedom, just like the hand of the ubiquitous Mod-8 master-slave manipulator (minus the grasp motion, obviously). In the ANL TV2, the head-cocking motion was intentionally left out because it is seldom used by an operator and presents no new view of the scene. The up-and-down and side-to-side translational motions of the whole head are particularly useful in helping the operator gain depth perception. The back-and-forth degree of freedom permits the operator to move closer to the work when desirable and vice versa.

The ANL TV1 camera was closely coupled to the motions of the operator's head. Experience showed this was undesirable because the slightest motion would be communicated to the camera, resulting in picture blurring. Later, on TV1 and TV2, a deadband of approximately 10° was permitted in the head's pan-and-tilt motions along with equivalent translational "play" in the other three degrees of freedom.

A radically new approach to providing the operator with both a wide field of view and high resolving power has been developed for DoD by the TRG Division of Control Data Corp. In the TRG concept the TV image in the central 8° of the field of view is eight times larger than the wide-field range image which occupies 68°. In other words, a magnified image is superimposed upon the wide field of view.

In the oculometer and the various other devices that detect eye motions we have a signal source that can give us even finer control over remote viewing equipment. It is not desirable to convert every flicker of the eye into a command signal to a TV camera, but gross motions of the eyeball might profitably be harnessed to a camera-pointing control system. This type of control would be useful if the TV camera (or some other visual sensor) had a very narrow field of view. When one already has a 30° field of view (e.g., the ANL TV2), most targets within "eyeball range" are already before the operator on the TV screen.

The teleoperators of the future that are dispatched to explore planets and the undersea by proxy, leaving man behind on Earth, will probably carry viewing systems based on the television systems control technology pioneered by Philco and Argonne National Laboratory. In particular, the ANL master-slave TV2 television system, when combined with the force feedback (feel) of electric master-slave arms and hands, is one of the most intimate examples of sensory integration we have in man-machine systems.

ACOUSTIC SENSORS

Sound provides a sensory channel to the operator's brain that is separate and distinct from the visual and "feel" channels that predominate in most teleoperator work. Sound can thus serve well for alarm signals, activated, say, by a microphone near the manipulator hands to tell the operator that something has been dropped. The auditory sensory channel requires a much smaller bandwidth than TV.

Sound also can be used to "illuminate" a target (to use radar terminology). To illustrate, sonar gives range, range-rate, and directional information. Even better, "imaging" sonars allow the operator to "see"—crudely—in the ocean depths despite murky palls of sediments that would render visual viewing systems useless.

Several contemporary hot-cell manipulatory systems, such as Minotaur, incorporate microphones as signal pickups to warn of dropped equipment, malfunctions, collisions, etc. Such applications of sound are useful but strictly supplementary in character.

Kama, Klepser, and others have experimentally evaluated sound as a means of improving the performance of a manipulator operator (refs. 110 and 111). In several experiments they employed Mod-8 mechanical master-slaves and put subjects through simple manipulatory tasks using vision supplemented by microphones. Such variations as monaural sound, stereo sound, white noise that masked all other sounds, and earplugs were tried. The gen-

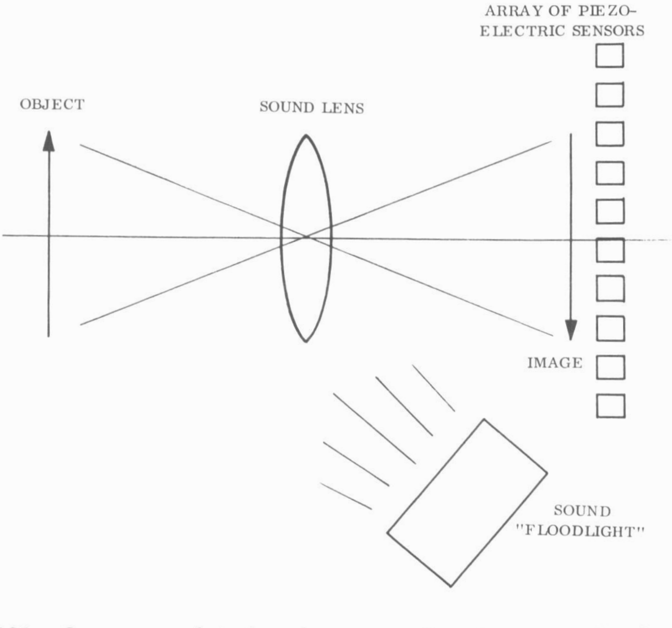

FIGURE 126.—One approach to imaging sonar. Sound source "illuminates" the target arrow; reflected sound waves are focussed onto an array of piezoelectric crystals by a sound lens; the crystals are then scanned either electronically or by an electron beam.

eral conclusion from human-factors studies like these is that the auditory channel is of little if any value to the operator, *unless* the task and microphones are specially designed to provide *significant* auditory cues.

Imaging sonar appears to hold more promise for teleoperators than simple microphones. An imaging sonar is analogous to television except that ultrasonic sound (around 500 kc) substitutes for light. Because the wavelengths of these sound waves are so much larger than those of light, image resolution will be worse. But amidst clouds of sediment, sound will penetrate where light will not. A number of projects in this country and abroad are directed toward refining "vision with sound."

An imaging sonar might work like this: a sound transmitter (floodlight analog) would illuminate the target area and manipulator arms (fig. 126). Reflected sound waves would be focussed with a sound lens on an array of tiny hydrophones (perhaps small piezoelectric crystals), to form an image of the scene; the crystal array would then be scanned by an electron beam or by phase techniques (similar to phased radar arrays). The electronic signals then could be fed to a cathode-ray tube to create a visual image of the scene for the operator.

Ultrasonic sound signals are attenuated more rapidly in seawater than conventional sonar signals which have ten times the wavelength. Nevertheless, they easily penetrate ten or twenty feet. Conventional sonar could, of course, locate the target in the first place.

Sound lenses must have large diameters to focus the incoming, long-wavelength sound waves into a sharp image. At 500 kc, an eight-inch lens is needed to provide a resolution of 1°—a very coarse image by optical standards. Sound lenses are made from plastic or a liquid, such as carbon tetrachloride, encased in a hollow plastic lens.

Before imaging sonars can be used to guide manipulator operations on the sea bottom, much more development work must be completed.

TOUCH SENSORS

The touch sense has already been made an integral part of teleoperator technology in terms of primitive microswitches and the more sophisticated bilateral master-slaves. A bilateral teleoperator, with its force feedback, can locate a target and reconnoiter it crudely with touch. It can also evaluate the target from the kinesthetic point of view; that is, it can estimate weight and resistance to motion.* But there are other aspects of the touch or tactual sense channel that need exploring, such as shape and texture recognition. These are beyond the reach of force-feedback systems with only seven degrees of freedom.

One way to approach the sensing of shape and texture is through the addition of more bilateral degrees of freedom in the teleoperator hand. To a very limited extent, Handyman does this with its coarse "finger" articulation. A curved surface can be distinguished from a flat surface in this way. Greater articulation, of coarse, would refine the information fed back to the operator. There are practical limits, however, to the number of servoed finger joints one can put in a hand of normal size.

The next logical thought is to distribute dense "tactual" arrays of tiny force transducers over the teleoperator hands and fingers. Such an array might be modelled after the piezoelectric grip sensors that have been incorporated in the jaws of some unilateral manipulators. The totality of force signals generated by such a tactual array would depend upon the shape of the object being held and, if the transducers are small enough, upon the object's texture or roughness. In practice, the array of piezoelectric crystals could be scanned by an electron beam and the electric signals could then be rendered as a visual display or, even better, as displacements or forces on the surface of the master hand. A true bilateral master-slave hand/finger surface with hundreds of degrees of freedom is possible in principle.

Some other potential tactual transducers are air jets, tiny strain gages, and rubber fabricated with dispersed carbon. Bliss, at Stanford Research Institute, has investigated piezoelectric and air-jet approaches under NASA and Air Force contracts (ref. 112).

Another class of transducers that has a potential for yielding tactual information depends upon the generation of visible effects through the deformation of a continuous rather than quantized "sensitive" surface. Moiré patterns and photoelastic effects immediately come to mind. Sheridan's group, at M.I.T., has explored several possibilities for NASA (refs. 113 and 114). The basic approach involves illuminating the deformed sensitive surface, as shown in fig. 127, detecting the resulting pattern on a TV camera watching through a fiber-optic bundle, and then displaying it to the operator on a TV screen. Besides Moiré patterns and the various photoelastic effects, one might use pliant opaque "skin"

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*The tactual (touch) sense differs from the kinesthetic (proprioceptive) sense.

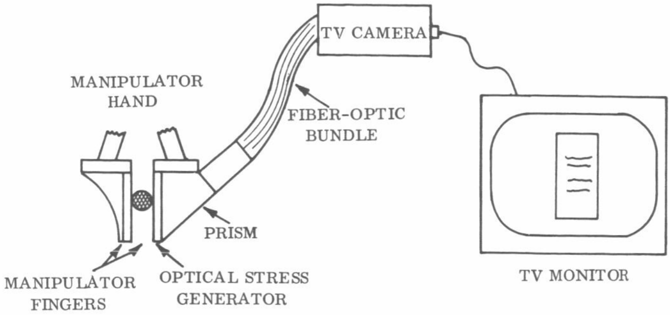

FIGURE 127.—Schematic diagram of an optical touch sensor. Photoelastic stress pattern generated by pressure on plastic or crystal-arrayed finger liner is monitored by TV (adapted from ref. 113).

with a mirror surface on its inside. By projecting a geometric pattern on the mirror surface from below, surface distortions due to the pressure of the target can be discerned as pattern distortions by the operator watching through the TV camera. The major difficulty with these "deformation" sensors is that the operator must be educated in the art of interpreting Moiré and photoelastic patterns. The relationship between the patterns and the shape of the grasped object is frequently subtle and quite artificial compared to the more direct bilateral feel of the object through force feedback.

One can only guess the practical effectiveness of deformation devices while they remain in the research phase. Obviously, something better than force feedback will be needed as teleoperators are applied more widely.

Man's visual and touch senses are the most useful of all his senses in projecting his natural dexterity through barriers and across distances. Considerable progress has been made in both areas in the last two decades. Examination of the other senses shows that ordinary listening does not seem to be of much use, though sound is promising as a target illuminator underseas. Taste, smell, and the other less-well-defined human senses apparently have had no roles in the advancement of teleoperators. The major areas for sensory development seem to be (1) in the closer *visual* coupling of man to the working area and (2) the many-fold multiplication of the amount of force or tactual information reaching the operator. The improvement of man's "presence" or involvement in a hostile environment or at some distant place depends upon better seeing and feeling.

CHAPTER 7

Teleoperator Terminal Devices

If teleoperator hands were truly close approximations of human hands, hammers, saws, pliers, and other common tools could be used without modification. Teleoperator hands, however, will not be dexterous enough for many years to handle these tools proficiently. Tool-handling deficiencies now are partially remedied in three ways:

1. The rather crude, general-purpose teleoperator hands are replaced by specially designed tools that attach to the teleoperator wrists or, more often, by off-the-shelf tools modified so that they can be handled effectively by general-purpose hands.
2. The teleoperator is specially designed for easy tool interchange. Generally, this means that a rack must be supplied from which the teleoperator arm can pick up and replace tools in the proper orientation.
3. The task is designed with an eye to manipulator capabilities and limitations. Insistence upon captive nuts and bolts and special fixtures for holding dismantled parts are examples of such foresightedness.

The more specialized the task the more foresighted one can be, and the more specialized and effective one can make the hand and tool combinations. Action in emergencies, one of the teleoperator stocks in trade, cannot be thought out with as much precision, however, as the dismantling of the NERVA nuclear rocket engine. If teleoperators are to achieve their full potential, hands and tools that do the work must be designed with great care.

TERMINAL DEVICES

A terminal device is whatever is at the end of a teleoperator wrist. It is the physical interface between the teleoperator and the task itself. It may be either a general-purpose "hand" or a special-purpose "tool."

The word "hand" applies to both the human-looking artificial hands that terminate many prostheses and the simple vise-like jaws on master-slave manipulators. The vise-type or parallel-jaw hand is by far the most common. As the jaws (also called "tongs" or "fingers") move toward or away from one another, they maintain their parallel relationship. Rods and other round objects twist easily between these plane surfaces. To prevent this, the jaws are sometimes notched or padded with a resilient material (fig. 128). In most hands, the jaws or fingers are remotely interchangeable.

The second major type of manipulator hand is the "hook" or "hook-and-anvil hand" (fig. 129). Most unilateral manipulators use these interchangeably with the parallel-jaw hand. The preferred hook-type hand has a stationary anvil and movable notched "finger." In the unilateral electric manipulator, an electric motor pulls the finger toward the anvil.

Some jaws close like scissors, but flat jaws then are usually replaced by curved fingers similar to old-fashioned ice tongs. This type of hand is called a "grapple" or "claw" and is used most frequently in underseas work (fig. 20).

The "clamshell scoop" is also of marine origin, having been

FIGURE 128.—A Mod-8 hand with notched jaws for holding cylindrical objects. (Courtesy of J. Burton, Atomics International Division, North American Aviation, Inc.)

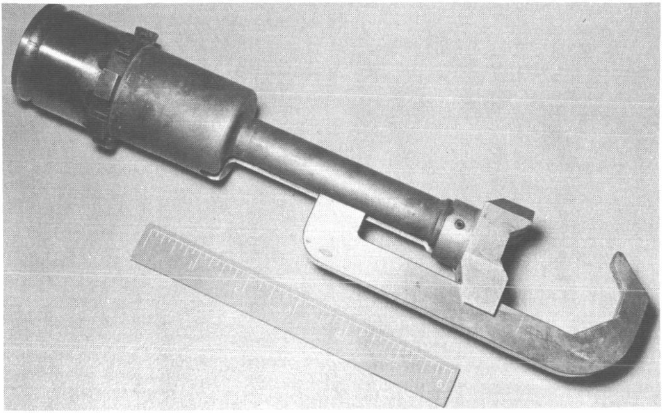

FIGURE 129.—A hook-and-anvil hand with movable hook. (Courtesy of R. Karinen, Programmed nad Remote Systems Corp.)

installed on Cousteau's *Diving Saucer*. The clamshell scoop opens and closes like a ring of flower petals. For this reason, it is also called a "petal," "blossom," or "orange-peel" hand (ref. 115). A clamshell scoop can grasp objects as well as gather samples of mud and sand.

In a conscious attempt to utilize experience in the prosthetics field, a few organizations, such as the University of California's Livermore Laboratory, have substituted prosthetic hooks (fig. 68) for vise-type hands on conventional master-slave manipulators. The prosthetic hook has proven to be better adapted to handling irregular objects and may eventually replace the vise- and hook-type hands in some applications.

With only single-degree-of-freedom hands, manipulator operators are often surprisingly deft. Part of the credit, however, belongs to the tool designers.

TERMINAL TOOLS

Tools can be plugged into a manipulator wrist to replace the general-purpose hand. Obviously, these tools must be specially constructed to mesh with the fittings, gears, and drive shafts of a particular teleoperator wrist. Specialization makes them expensive but more effective in narrow lines of work.

Hand-held tools comprise another class. How can a choice be made between the two types of tools for a given application? Some considerations are:

1. Is the hand strong enough to handle the contemplated tool? If not, a specially designed wrist-attached tool may be lighter than a hand-held general purpose tool. The wrist joint can doubtless handle more weight than the fingers of a hand. The same kinds of considerations apply to power, torque, and grip forces.
2. Can the power be conveniently switched on and off? When the power comes from the manipulator wrist, the switch is built into the manipulator controls.
3. In an emergency, could the wrist-attached hand be readily exchanged for a general purpose hand?
4. Is there a chance that the wrist-attached tool might get stuck or somehow wedged in the work so that the arm could not be retracted?
5. Which approach will get the job done better in terms of time, cost, and other mission figures of merit?

In the nuclear industry, where these questions first arose, the hand-held tool is favored. Part of this preference is because the great bulk of hot-cell manipulators are mechanical master-slaves that have no motor drives at the slave wrist. Indeed, the question of the tools required for a mission may help determine the kind of manipulator finally selected. If the mission involves a great deal of bolting and unbolting, an electric or hydraulic arm with a special wrench replacing the hand may be more effective than a power wrench held by a master-slave. The force-reflecting master-slaves are usually superior in the matter of tool manipulation and control. For example, sawing without a sense of feel might lead to saw binding and breakage.

If the decision is in favor of a wrist-attached tool, a rather good selection of tools is commercially available. Others can be readily built from proven designs, particularly for unilateral manipulators. The more important of these are listed in table 21 (adapted from ref. 115). Figure 130 illustrates a wrist-attached tool.

HAND-HELD TOOLS

Hand-held tools may be specially built for manipulator use, or commercially available tools modified slightly to make them easier to handle with the single degree of freedom available in the teleoperator hand.

Some of the simpler tools such as pliers may be permanently fitted with manipulator fingers, after the fashion shown in fig. 131. Such an assembly is termed an "integral hand-tool combina-

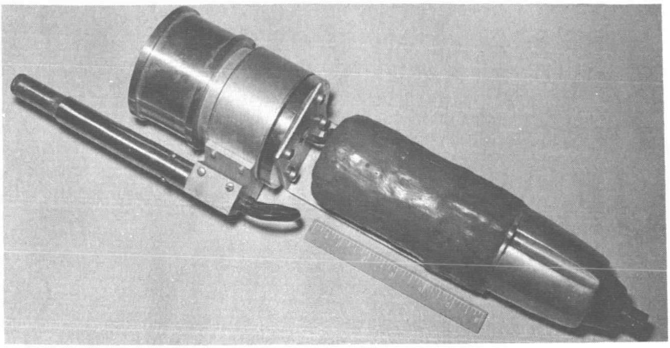

FIGURE 130.—A motor-driven impact wrench that replaces a general purpose hand on a PaR–3000 unilateral manipulator. (Courtesy of J. Burton, Atomics International Division, North American Aviation, Inc.)

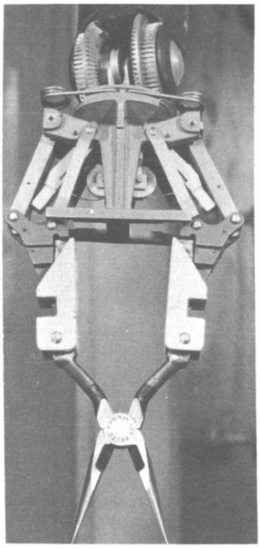

FIGURE 131.—Longnose pliers attached to a pair of interchangeable manipulator fingers. This is an example of an integral hand-tool combination. (Courtesy of J. Burton, Atomics International Division, North American Aviation, Inc.)

tion." It has the disadvantage of requiring finger changes each time the tool is used.

More common and more versatile is the "adapter block." An adapter block is simply a chunk of metal with finger slots milled on two sides for grasping with the vise type of manipulator hand.

The adapter block can be permanently attached to many tools, such as saws, grinders, and even radiation meters. Many of these adaptable tools are listed in table 21; a few are illustrated in figs. 132, 133, and 134.

Not only must an adapter block be provided, but the switches on commercially available power tools must be dismantled and connected in a spot where the manipulator operator can reach them.

A good tool rack promotes effective tool use, especially when one is working with a single arm in space or under the ocean. Tools should be stored in a position in which the manipulator

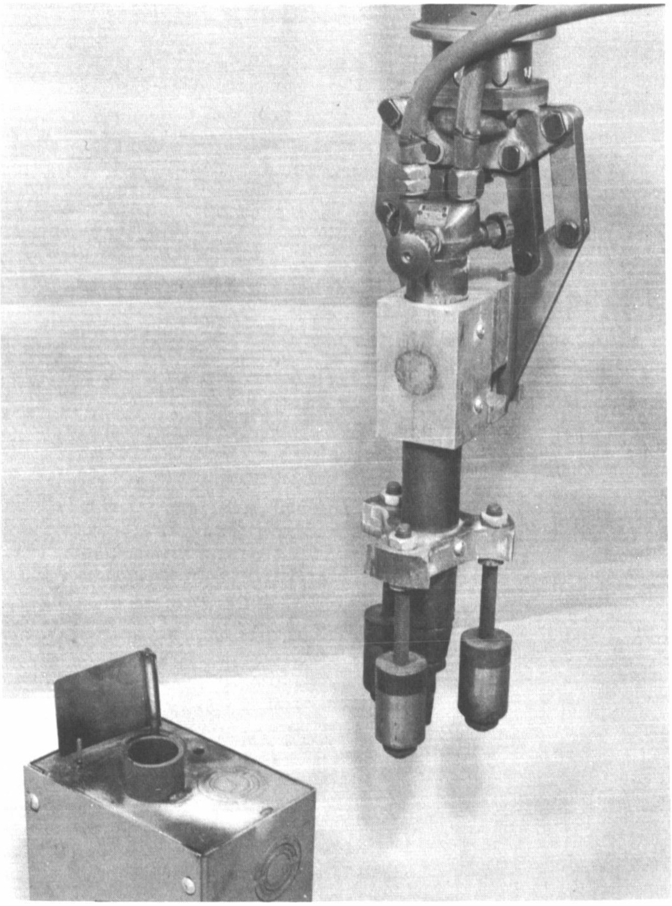

FIGURE 132.—A gas cutting torch with added adapter block for easy manipulation. (Courtesy of J. Burton, Atomics International Division, North American Aviation, Inc.)

TABLE 21.—*Tools Used in Nuclear Reactor Maintenance and Disassembly.*

Tool	Tool Used	Method of Support				Powered electrically?
Impact wrench	Bolting, drilling, rotary actuator	1	2	3	4	Yes
Band saw	Cutting, tubing and light structure	1	2	.....	4	Yes
Circular saw	General-purpose cutting using abrasive "cut-off" type blade	1	.....	3	4	Yes
Drill	Bolt and nut running, drilling, rotary actuator	1	2	.....	.....	Yes
Grinder	Same as circular saw above and grinding	.....	.....	3	4	Yes
Power screwdriver	Same as drill motor above but higher torque	1	.....	3	.....	Yes
Reciprocating saber saw	Starting cut in center of sheet or plate—general cutting of metals and plastics	1	.....	3	.....	Yes
Nibbler	Cutting metal, light plate and sheet	1	2	3	.....	Yes
Hydraulic guillotine	Cutting, shearing, crimping light tubes, bar stock, wire rope, electrical multi-conductor cable	.....	2	.....	.....	Yes
Explosive guillotine	Cutting and crimping	.....	2	.....	4	Explosive
Vacuum cleaner (drum type)	Clean up following sawing	.....	2	.....	.....	Yes
Vacuum cleaner (portable)	Clean up and as blower	.....	.....	.....	4	Yes
Can-lid crimper	Crimping cans of toxic waste or specimens	.....	2	.....	.....	Yes
Oxyacetylene cutting torch	Flame cutting	.....	.....	3	.....	No
Caliper	Special tool for precision measurement	.....	.....	3	.....	No
Typical "pin handling" tool	Handling of pins on nuclear reactor fuel element	1	.....	.....	.....	By hand
Radiation survey meter	Surveying for radioactive materials	1	.....	3	.....	Self

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1. Hook-and-anvil hand.
2. Shoulder hook.
3. Parallel-jaw hand.
4. On wrist in place of hand.

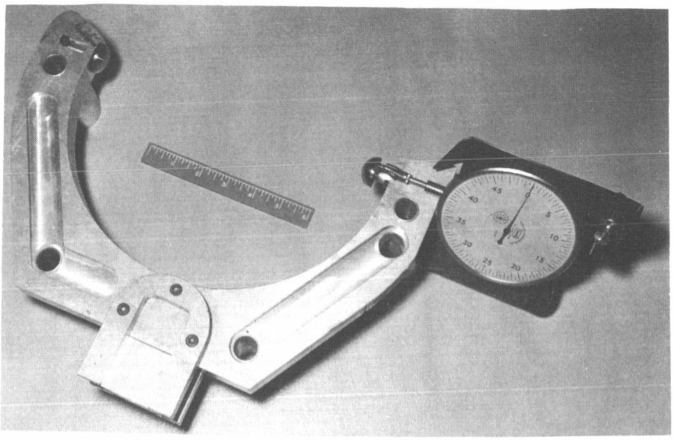

FIGURE 133.—Precision measuring device for manipulator use. It is read by TV. Note the grooves in the adapter block. (Courtesy of J. Burton, Atomics International Division, North American Aviation, Inc.)

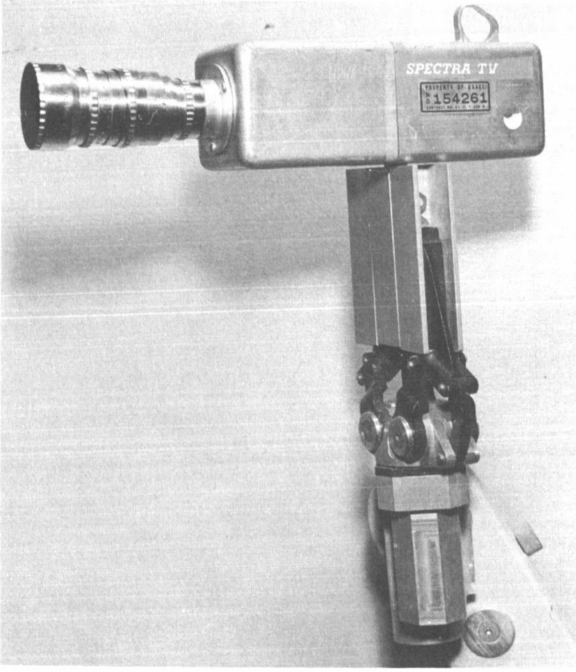

FIGURE 134.—Miniature TV camera with attached adapter block. (Courtesy of J. Burton, Atomics International Division, of North American Aviation, Inc.)

hand can firmly grasp them, extract them from the rack, and replace them. A dropped tool in a hostile area may be a lost tool.

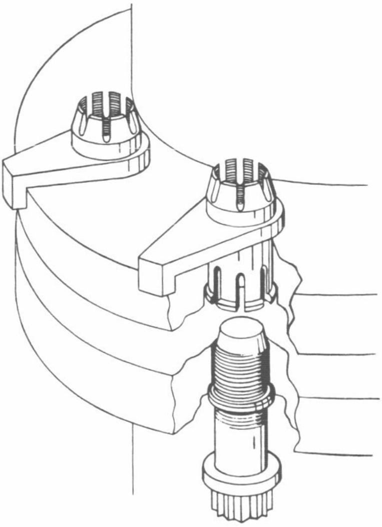

FIGURE 135.—Drawing of a typical captive nut and bolt assembly.

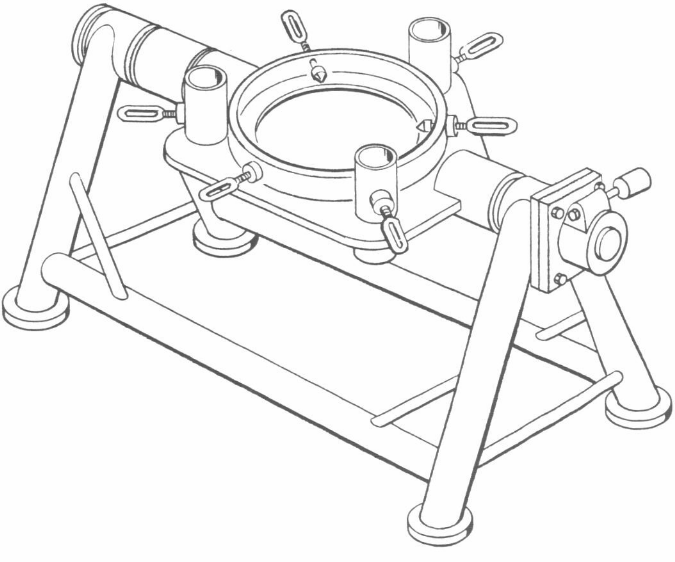

FIGURE 136.—Typical stand or fixture for holding dissembled pieces of equipment. This particular stand is designed to hold the lower thrust structure from a nuclear rocket.

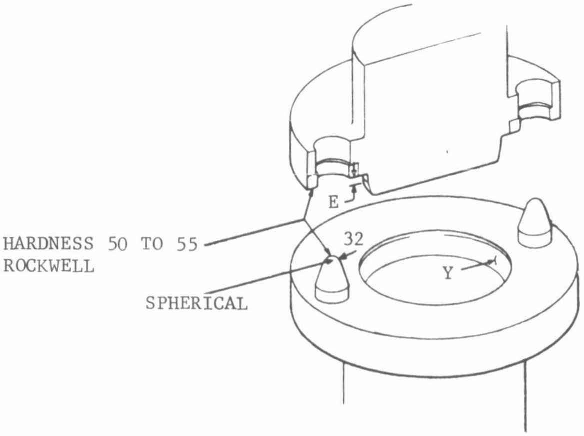

FIGURE 137.—Typical pilot pins and guide ring for easing equipment assembly.

TASK DESIGN

If a machine, say a nuclear rocket engine, is being disassembled, each piece must be designed so that the manipulator can (1) reach it, (2) unfasten it easily, (3) grab it firmly, (4) extract it and lift it clear, and (5) set it down in a position and attitude that permit easy recovery (refs. 116 and 117). Naturally, the same points apply to assembly, but in reverse order.

A number of mechanical devices are available to help the manipulator operator in assembly-disassembly sequences. In the first category are such things as captive nuts and bolts that cannot fall to the floor and be lost (fig. 135). They also promote reassembly. Many electrical and hydraulic "quick disconnects" are amenable to remote handling. In the second category are the so-called "fixtures." These are special stands that hold the manipulator-deposited parts in the proper positions for manipulator recovery (fig. 136). Finally, there are the guide pins and grooves that materially aid the operator in correctly positioning components during reassembly operations (fig. 137). All of these strategems require the foreknowledge and cooperation of the machine's designer long before remote operations begin.

CHAPTER 8

Conclusions and Forecast

Thousands of teleoperators have been built and used successfully in handling radioactive materials, helping the handicapped, and working on the ocean bottom. But these teleoperators are poor and incomplete extensions of man, with only a small fraction of man's dexterity and man's many degrees of freedom. Such is the current state of the art, but our survey has noted many scattered harbingers of growth. This growth will meet demands that man cannot fulfill without machine aid and it is being encouraged by many new technical developments.

Such developments are seldom breakthroughs when taken separately. Together, however, recent advances are giving us the ability to build a new generation of teleoperators. Their subsystems are benefitting directly from aerospace and related technology as indicated below:

Teleoperator Subsystem	*Developments Benefitting Teleoperators*
Actuator subsystem	Miniature motors, magnetic muscles, stepping motors
Sensor subsystem	Miniature TV cameras, tactual sensors, sonar imagers, infrared devices
Control subsystem	Digital control techniques, computer-generated visual displays, computer control systems (supervisory control), EMG
Communication subsystem	PCM refinements, lasers, miniature equipment
Computer subsystem	Fast, lightweight computers and memories
Power subsystem	Miniature batteries, lightweight solar and nuclear power plants
Environment-control subsystem	Space life-support systems
Structure subsystem	Strong lightweight materials

It is tempting to predict which industry—and men, as a consequence—will benefit most from improved teleoperators. But radically new developments have a habit of becoming valuable where least expected.

Some "fallout" is highly probable in the prosthetics field as engineers begin to apply new materials, better power supplies and control techniques. Public services may increasingly need teleoperators to handle the more dangerous byproducts of our civilization. But these are down-to-earth and rather conservative thoughts.

Plans for harnessing teleoperators need not and must not be limited by today's crude mechanical arms with their few degrees of freedom or by today's primitive walking machines and exoskeletons. The man-controlled teleoperator enables man to conquer distance, high temperatures, high pressures, noxious atmospheres, and other recalcitrant environments on the periphery of his narrow domains.

Scientific gadgetry may some day project a human being to wherever he wants to be and faithfully duplicate that spot's environment as well as the operator's actions. One can even conceive of a great surgeon operating on a patient a thousand miles away via a teleoperator with great dexterity and acute tactual feedback. The augmentation and extension of man by teleoperator will also help tap new lodes of raw materials and food supplies, such as those now locked in the deep oceans. A teleoperator can place the surface of Mars or the ocean floor at the scientist's fingertips. Conceivably, man-machine symbiosis can make man a superman, either on the spot he occupies or on the other side of the universe.

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Glossary of Acronyms and Special Terms

Adelbert: A Tulsa inventor's privately manufactured electric unilateral manipulator, circa 1951.

Aluminaut: A manned submersible carrying General Electric electrohydraulic unilateral manipulators. Built by Reynolds Co.

Alvin I: Small manned submersible, named after Allyn Vines of Woods Hole, Mass., and built by Electric Boat. Equipped with unilateral electric manipulators built by General Mills and Litton Industries.

AMF: American Machine & Foundry, York, Pa., a major manufacturer of mechanical master-slaves.

ANL: Argonne National Laboratory, an AEC installation near Chicago.

Asherah: A small, manned submersible being built by Electric Boat for the University of Pennsylvania. Manipulators will be employed for archeological research.

Autec I and II: Small, manned submersibles being built by Electric Boat for the Atlantic Undersea Test and Evaluation Center. Manipulators used for undersea maintenance and repair.

Autofab: A General Mills preprogrammed industrial manipulator.

Bat: A tow tractor with a shielded cab developed by the Air Force for nuclear emergency work.

Beaver: A small, manned submersible concept developed by North American Aviation. Mounts electrohydraulic unilateral manipulators.

Beetle: A manned, shielded tank-type vehicle developed by the Air Force for nuclear emergency work. Two large, electric unilateral manipulators.

Brute: Beyond Road Utility Tool Extender.

BNL: Brookhaven National Laboratory, an AEC installation on Long Island.

CAM: Cybernetic Anthropomorphic Machines. Acronym originated by General Electric to describe teleoperators.

CRL: Central Research Laboratories, Red Wing, Minn., a major manufacturer of teleoperators (mechanical master-slaves).

CURV: Cable-Controlled Underwater Research Vehicle. A teleoperator-equipped submersible developed by the Naval Ordnance Test Station (NOTS) for weapons recovery.

Denise: Small, manned submersible developed by Cousteau; the forerunner of *Deep Star*.

Deep Quest: A Lockheed manned submersible.

Deep Star: A small, manned submersible developed by Cousteau and Westinghouse. Manipulator equipped.

Diving Saucer SP–300: Another Cousteau manned submersible. Equipped with a clamshell manipulator.

DOWB: Deep Ocean Work Boat, a manned submersible developed by General Motors. Equipped with PaR electric unilateral manipulators.

DSVR–1: Deep Sea Rescue Vehicle–1. A large, air-transportable, Navy rescue submersible, now in preliminary design stage. Manipulator equipped.

DSSP: Deep Submergence Systems Project; a Navy project.

DSSRG: Deep Submergence Systems Review Group; a Navy study group formed after the *Thresher* incident.

EBR II: Experimental Breeder Reactor II; an AEC reactor experiment in Idaho. The associated fuel-cycle facility incorporates considerable automatic and remote-control equipment.

EIV: Engine Installation Vehicle. A vehicle used at NRDS for remotely installing and removing the NERVA nuclear rocket engine from its test stand. Equipped with two PaR unilateral electric manipulators.

EMG: Electromyographic; an adjective describing the use of body potentials for controlling prosthetic devices.

E-MAD: Engine Maintenance, Assembly, and Disassembly building at NRDS, in Nevada. This building has a very large hot cell with many manipulators for remotely handling the NERVA nuclear rocket engine.

ESMRO: Experiments for Satellite and Material Recovery from Orbit. A study program at NASA's Marshall Space Flight Center.

E4A: The latest electric master-slave in a series developed by Argonne National Laboratory.

Fleximan: A preprogrammed industrial manipulator developed by United Fleximation Corp.

Garco: A privately built electric unilateral manipulator exhibited in Los Angeles circa 1953.

GEPUD: A tethered submersible—manipulator-equipped—proposed by Batelle Memorial Institute.

GPR: General Purpose Robot; a mobile manipulator built for nuclear operations at Savannah River.

Handyman: An electrohydraulic master-slave manipulator developed for the AEC by General Electric.

Happy Hippo: A DuPont explosives-handling device employing a simple manipulator.

Hardiman: An exoskeletal research project jointly sponsored by the U.S. Army and Navy.

Humpty Dumpty: A Douglas Aircraft egg-shaped space vehicle concept, with manipulators for maintenance and repair work in space.

Hydroman: An all-hydraulic manipulator developed by the AEC's Oak Ridge National Laboratory.

IMM: Independent Manned Manipulator; a study of orbital teleoperator vehicles by Ling-Temco-Vought and ANL for NASA's Marshall Space Flight Center.

Iron Hand: A preprogrammed industrial manipulator built by the Sahlin Engineering Co.

LASL: Los Alamos Scientfiic Laboratory, Los Alamos, N.M.

Little Ranger: A small, mobile manipulator for nuclear work, built by General Mills.

MAIS: Mechanical Aids for the Individual Soldier; a U.S. Army project involving human-augmentation concepts, such as Hardyman.

Man Friday: A memory-controlled space manipulator system proposed by Consolidated Controls for space repair and maintenance work.

Manipulet: A Salem-Brosius forging manipulator.

MAN II: An early General Electric master-slave.

Masher: An Air Force shielded vehicle for nuclear recovery work. No manipulators.

Maximan: A concept for extending man's capabilities through the use of teleoperators.

MCC: Manned Control Car. A shielded railroad car that serves as the engine for the EIV at NRDS, in Nevada.

Mermut: Small, manipulator-carrying submersible made by Vare Industries.

Mini-Manip: A small, mechanical manipulator developed by AMF Atomics.

Minotaur: Electric, unilateral manipulators combined with TV cameras into a bridge-crane-mounted teleoperator. Manufactured by General Mills and installed at BNL and LASL. Refitted with PaR electric, unilateral manipulators.

Mobot: (from mobile robot) Mobile teleoperators with electric unilateral arms plus TV cameras. Built by Hughes.

Modul-Arm: Electric Boat concept permitting a large number of different manipulator arms to be assembled from a few modular building blocks.

Mod 8: The ANL Model–8 mechanical master-slave, the most common teleoperator in existence.

MRMU: Mobile Remote Manipulating Unit; a remotely controlled mobile test bed built for the Air Force. FMC Corp. unilateral manipulators and TV cameras are mounted on vehicle.

MRH: Mobile Remote Handler; an early mobile manipulator design by General Mills for Sandia Corp., never built.

MSFC: Marshall Space Flight Center, a NASA installation at Huntsville, Ala.

MWP: Maneuvering Work Platform; an orbital vehicle concept studied by Ling-Temco-Vought for MSFC. Docking arms.

NERVA: Nuclear Engine for Rocket Vehicle Application; an AEC-NASA program.

NRDS: Nuclear Rocket Development Station, in Nevada.

NRTS: National Reactor Testing Station, in Idaho, an AEC installation.

NR–1: A small submersible being built by Electric Boat with Westinghouse unilateral manipulators.

O-Man: An overhead manipulator of the electric unilateral type at R-MAD.

OPS: Overhead Positioning System, used to position manipulators at E-MAD.

PaR: Programmed and Remote Systems Corp., St. Paul, Minn., a leading manufacturer of electric unilateral manipulators.

PaR–1: Small, mobile manipulator. Electric unilateral manipulator plus TV camera. Built by Programmed and Remote Systems Corp.

Pedipulator: A General Electric walking-machine concept.

Planobot: A preprogrammed industrial manipulator manufactured by Planet Corp.

Recoverer I: A small, manipulator-carrying submersible. Manipulator built by International Underwater Research Corp.

Remora: A Bell Aircraft concept for an orbital repair and maintenance vehicle carrying manipulators.

RESCUE: Remote Emergency Salvage and Clean Up Equipment; a concept for mobile remote manipulating equipment proposed by Programmed and Remote Systems.

R-MAD: Reactor Maintenance, Assembly, and Disassembly building at NRDS.

ROSE: Remotely Operated Special Equipment; an acronym applied to a pair of AEC seminars held in 1964.

RUM: Remote Underwater Manipulator; a tracked bottom crawler with an electric unilateral manipulator built by General Mills. RUM was developed for Scripps.

SCHMOO: Space Cargo Handler and Manipulator for Orbital Operations; an early Lockheed teleoperator concept.

Seapup: A small, manipulator-carrying submersible designed by General Mills for Woods Hole. Never built.

Serpentuator: (Serpentine Actuator) An electric teleoperator being developed at MSFC.

Slave Robot: A mobile manipulator utilizing the ANL electric master-slave concept.

SMRVS: Small Modular Recovery Vehicle System; a mobile manipulator proposed by General Electric for nuclear emergency applications.

SOLARIS: Submerged Object Locating and Retrieving Identification System; a Vitro underwater teleoperator concept for weapons recovery.

Space Taxi: An orbital teleoperator concept studied by Ling-Temco-Vought and ANL for MSFC. Mission was primarily maintenance, repair, and crew-cargo shuttle.

Spook: A radio-controlled bulldozer developed by Allis-Chalmers.

Theseus: The electronic, maze-running mouse built by Shannon, circa 1948.

Tool Dolly: A General Electric mobile manipulator at Hanford, Wash.

Trieste: A series of small submersibles carrying manipulators of various manufacture.

Unimate: A robot forging manipulator built by Consolidated Control Corp.

UNUMO: A suspended underwater teleoperator built by Hughes for offshore oil work. UNUMO possessed four arms plus a TV camera.

Versatran: A preprogrammed industrial manipulator built by AMF Atomics.

WMHS: Wall-Mounted Handling System; using General Electric electric unilateral booms and PaR manipulators at NRDS.

Yes Man: An early robot built by General Electric, circa 1956.

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