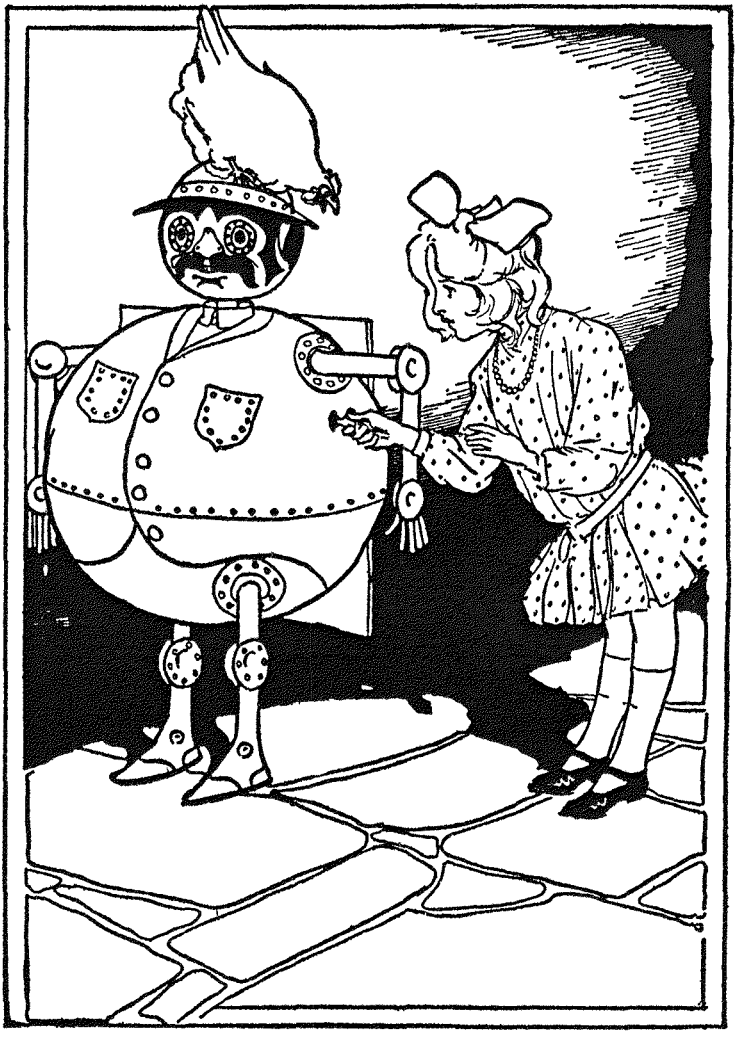

Teleoperators: Man's Machine Partners

by William R. Corliss

Nuclear energy is playing a vital role in the life of every man, woman, and child in the United States today. In the years ahead it will affect increasingly all the peoples of the earth. It is essential that all Americans gain an understanding of this vital force if they are to discharge thoughtfully their responsibilities as citizens and if they are to realize fully the myriad benefits that nuclear energy offers them

The United States Atomic Energy Commission provides this booklet to help you achieve such understanding.

UNITED STATES ATOMIC ENERGY COMMISSION

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James T Ramey
Dr. Clarence E. Larson
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Teleoperators: Man's

THE COVER This illustration from *Tik-tok of Oz* shows Betsy Bobbin winding Tik-tok, the most famous thinking machine in the land of Oz.

Machine Partners

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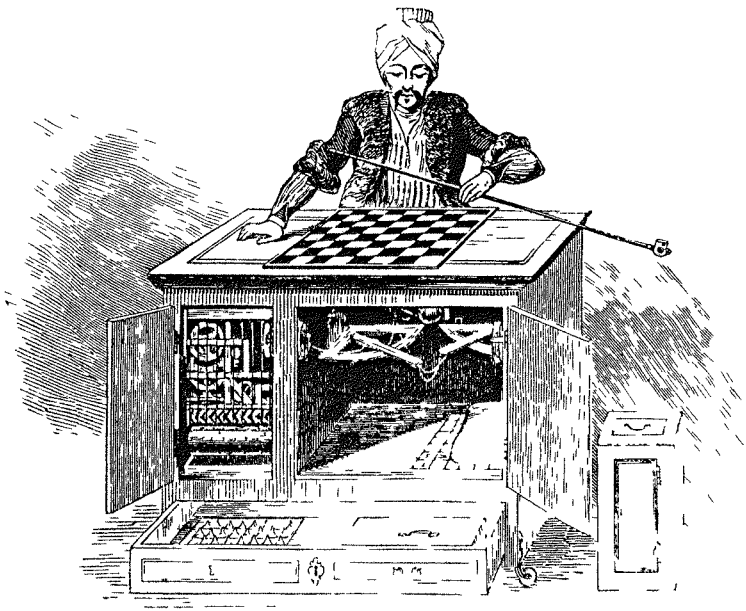


Baron Von Kempelen's chess-playing Turk.

THE TELEOPERATOR: A MAN-MACHINE SYNTHESIS

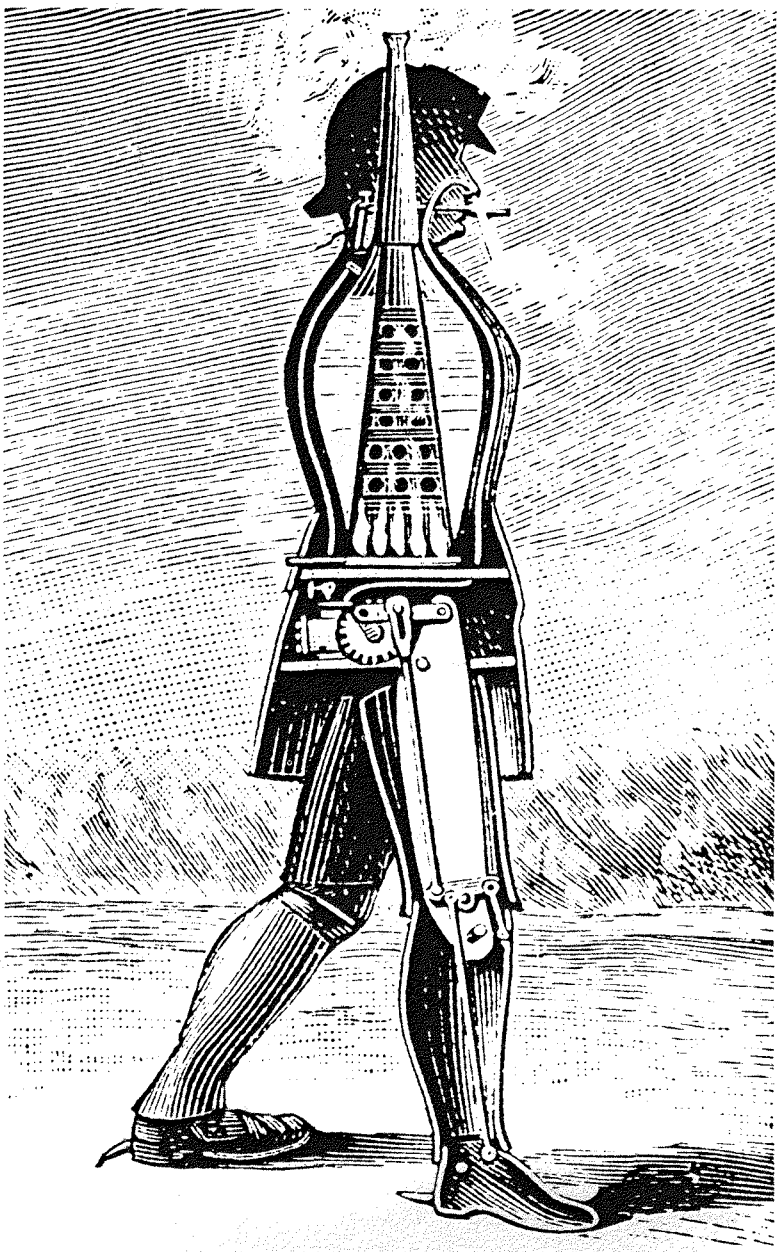
Early in the 19th century, Napoleon sat across a chessboard from a robot swathed in the robes of a Turk. Napoleon moved his chessmen into battle; the Turk did the same. Then, when Napoleon blundered three times in succession, the audacious machine swept the board clean with an iron hand.

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

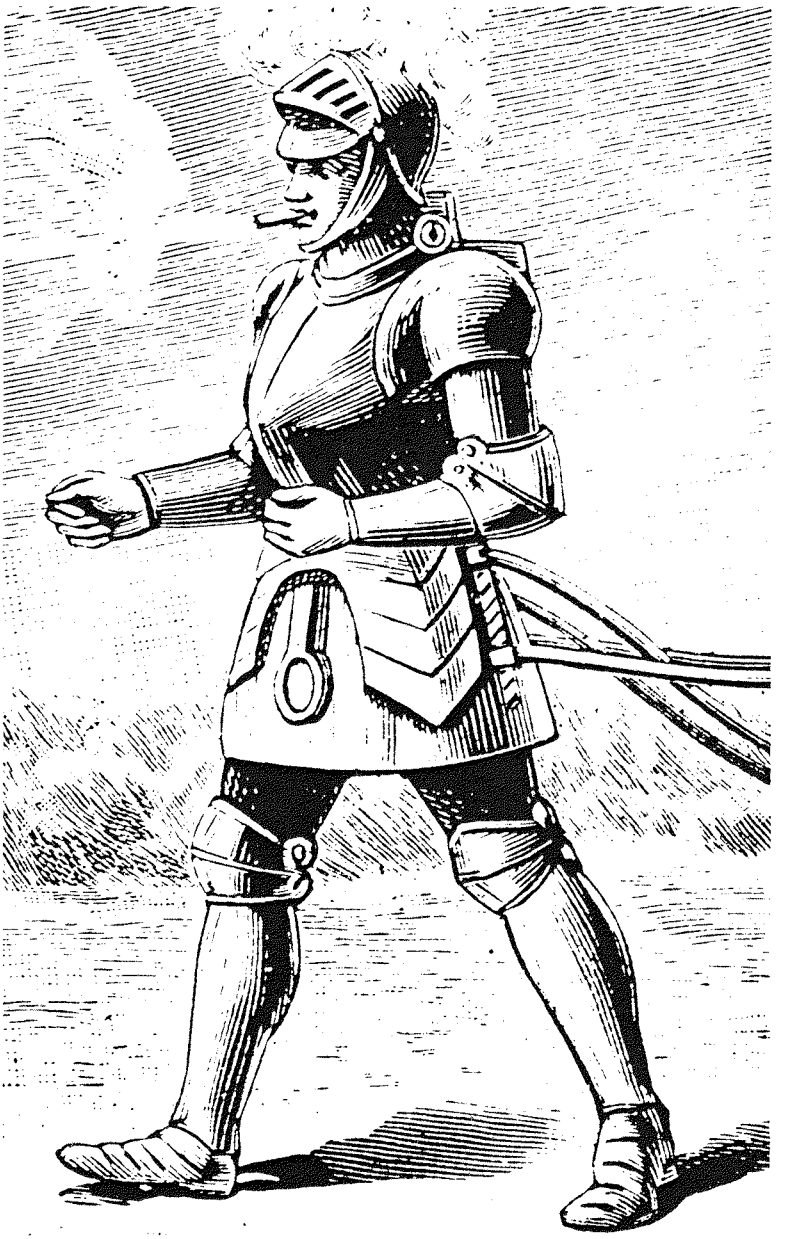
Indeed, man has always been fascinated by *robots*—machines that do his work and often look like him. He is scarcely less intrigued by machines that seem to think like him (*computers*)* and those machines that control themselves (*automatons*). Many are the basement inventors who have built machines that walk and talk like men, but these crude machines did not think or control themselves intelligently. It is in science fiction that the ultimate robots dwell. These sleek robots (often called *androids*) are computerized and thus have some ability to think. They are also autonomous; that is, they need not be controlled directly by man. The ultimate robot of fiction, superior in physical strength and mental capacity, runs the world for his human creators. In many wild tales these arrogant machines take over the planet (or the universe) completely.

Stimulating as science fiction is, it is not reality; the ultimate robot is a long way off. However, this fact should

*See *Computers*, another booklet in this series.



The "steam man" was invented by George Moore in 1893. A gas-fired boiler operated an engine of ½ horsepower, and the exhaust was

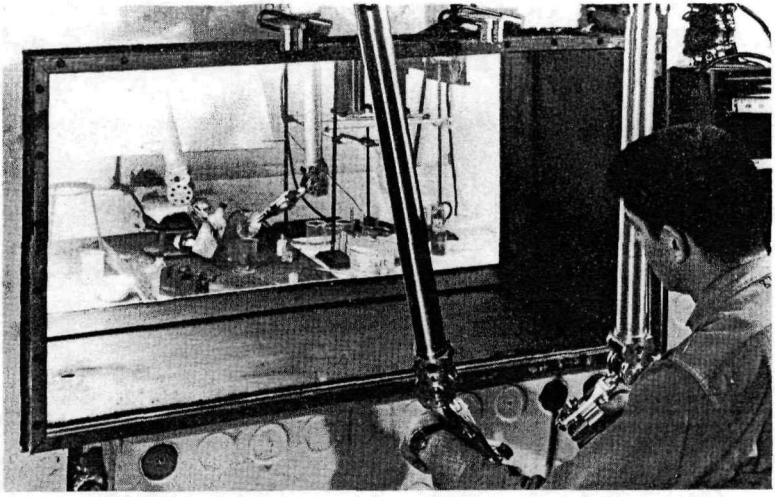


released through the helmet and cigar. It's walking speed was 7 to 9 miles per hour.

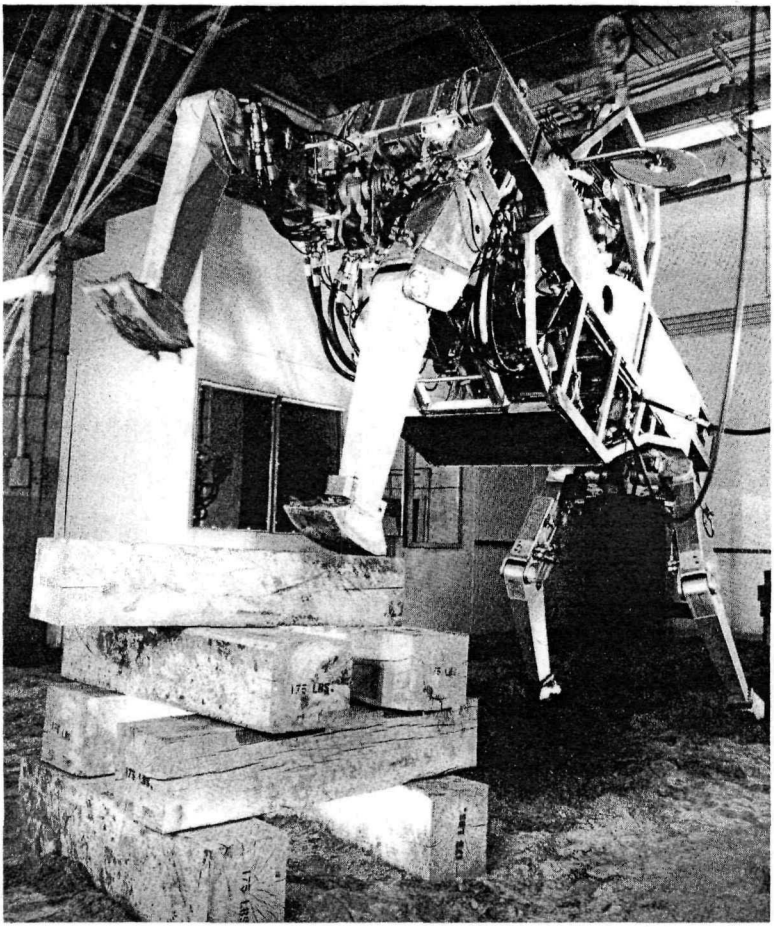
not dissuade us from building machines that can help man: machines that can take the place of men on the bottom of the sea, in dangerous coal mines, in mind-dulling industrial jobs, in all the dirty and dangerous tasks that still must be done by *somebody* or *something*. This booklet is about one of the "somethings". The "something" in this case is the *teleoperator*, a class of machines that augment man rather than replace him. Teleoperators have the ability to add to man's strength, his reach, and his ability to work in hostile environments.

The teleoperator is best defined by presenting examples of the four basic types:

1. Manipulators. These are machines that project man's unique ability to handle objects skillfully and to work with tools across distances and through barriers into hostile environments. Examples: The manipulators used on deep-sea submersibles and in radioactive hot cells, which are heavily shielded enclosures where radioactive materials are handled remotely.



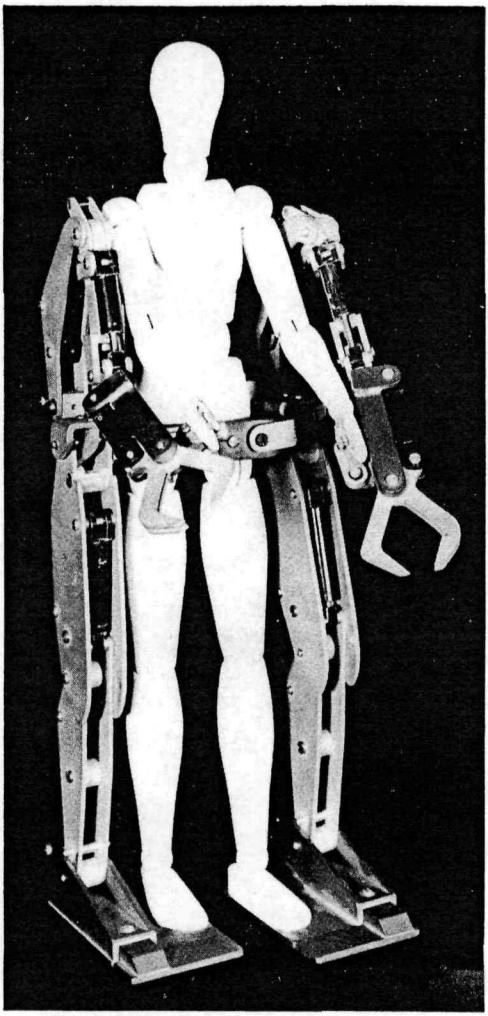
A technician manipulates radioactive material with master-slave hands in a hot cell.



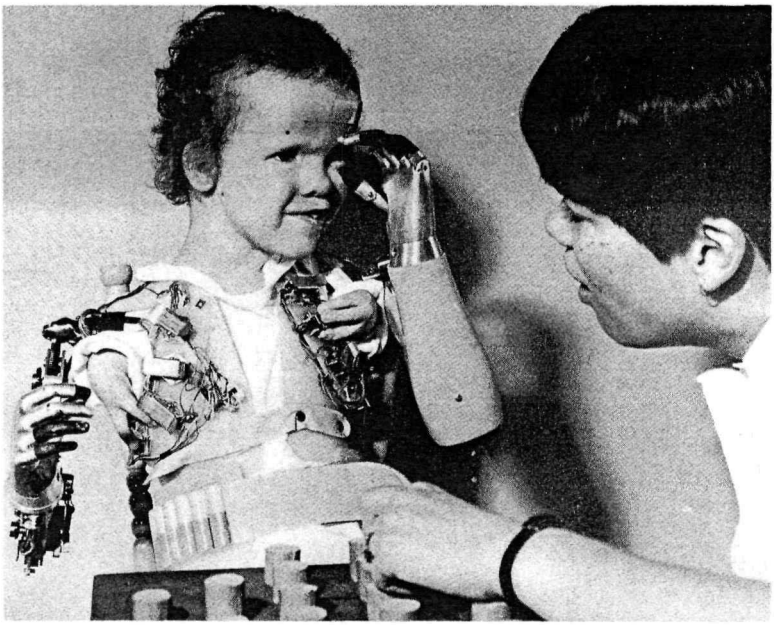
The Walking Truck could carry troops or cargo over terrain impassable to wheeled or tracked vehicles.

2. *Walking Machines.* Just as manipulators emulate an operator's arm and hand motions, walking machines follow the dictates of the operator's feet (and his arms if the machine is a quadruped). Walking machines are also called *pedipulators.* Example: The Walking Truck shown in the figure, which is a four-legged pedipulator controlled by the arms and feet of the operator. The Walking Truck was built for use in rough terrain where wheels would be useless.

3. *Man Amplifiers.* These are shell-like machines (exoskeletons) that surround human limbs and amplify their strengths. Man amplifiers combine the functions of manipulators and pedipulators. Example: The Hardiman man amplifier shown in the figure.



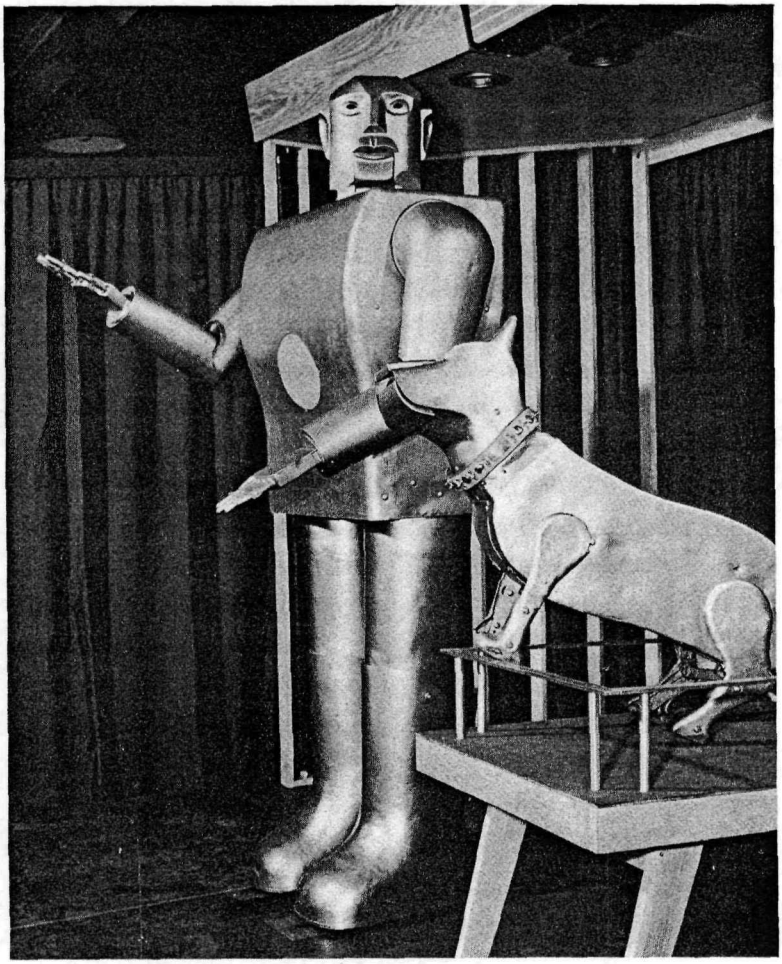
This set of "mechanical muscles", called Hardiman, will give a human being the strength of a giant and enable him to lift a 1500-pound load while exerting only a fraction of this force.



Electric arms used by a thalidomide victim. The arms are controlled by switches that the child activates with her fingers.

4. *Prostheses.* Artificial limbs are also teleoperators. Rather than amplifying the capabilities of normal people, a prosthesis helps the handicapped person to do things everyone else can do. Example: The artificial arms shown in the figure.

From the descriptions above, one sees that the important characteristics of teleoperators are that: (1) they duplicate the general-purpose, dexterous motions that help make man unique; and (2) they require the presence of a human operator who controls the machine most of the time. Thus, teleoperators are *not* autonomous; they do *not* think for themselves; and they do *not* necessarily resemble human beings. They are not robots. Teleoperators are simply machines that help men to do things they could not do ordinarily.



Electro and Sparko were automatons shown at the 1939 New York World's Fair.

FROM GROCER'S SHELF TO HOT CELL

The artificial limb is at least as old as the pyramids. Archaeologists have found numerous prosthetic devices among the medical wares of the ancient Egyptians. The first true manipulators were not very dexterous. Blacksmiths used them to hold the red-hot metal they were working with hammer and anvil. The tongs of the blacksmith were not very sophisticated but they did permit man to project his manipulator capabilities into a "hostile environment"—the heat of the forge. And not too long ago, in the old country stores, the grocer retrieved objects from his high shelves with long tongs, extending his reach and projecting his manipulatory capabilities across a distance. As long as man imposed these simple requirements on teleoperators, they, too, remained relatively simple.

Down through the centuries, most of the basement tinkerer's passion for building man-like (anthropomorphic) machines has concentrated on the robots, which are first cousins of teleoperators and which require much of the same technology. We see in the chess-playing Turk, for example, manipulatory devices potentially useful to modern man in helping him project his hands into hostile environments.

Entertaining, but just as frivolous, were the marvelous automatons built in the late 1700s by the famous Jaquet-Droz father-son team. Controlled by grooved rotating disks, the 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. (Their likenesses had been recorded beforehand in the grooved disks that controlled the automaton's motions. Such a machine would be called *preprogrammed* today.)

The delight that children and adults alike experience with man-like machines carries over to modern Disneyland, where

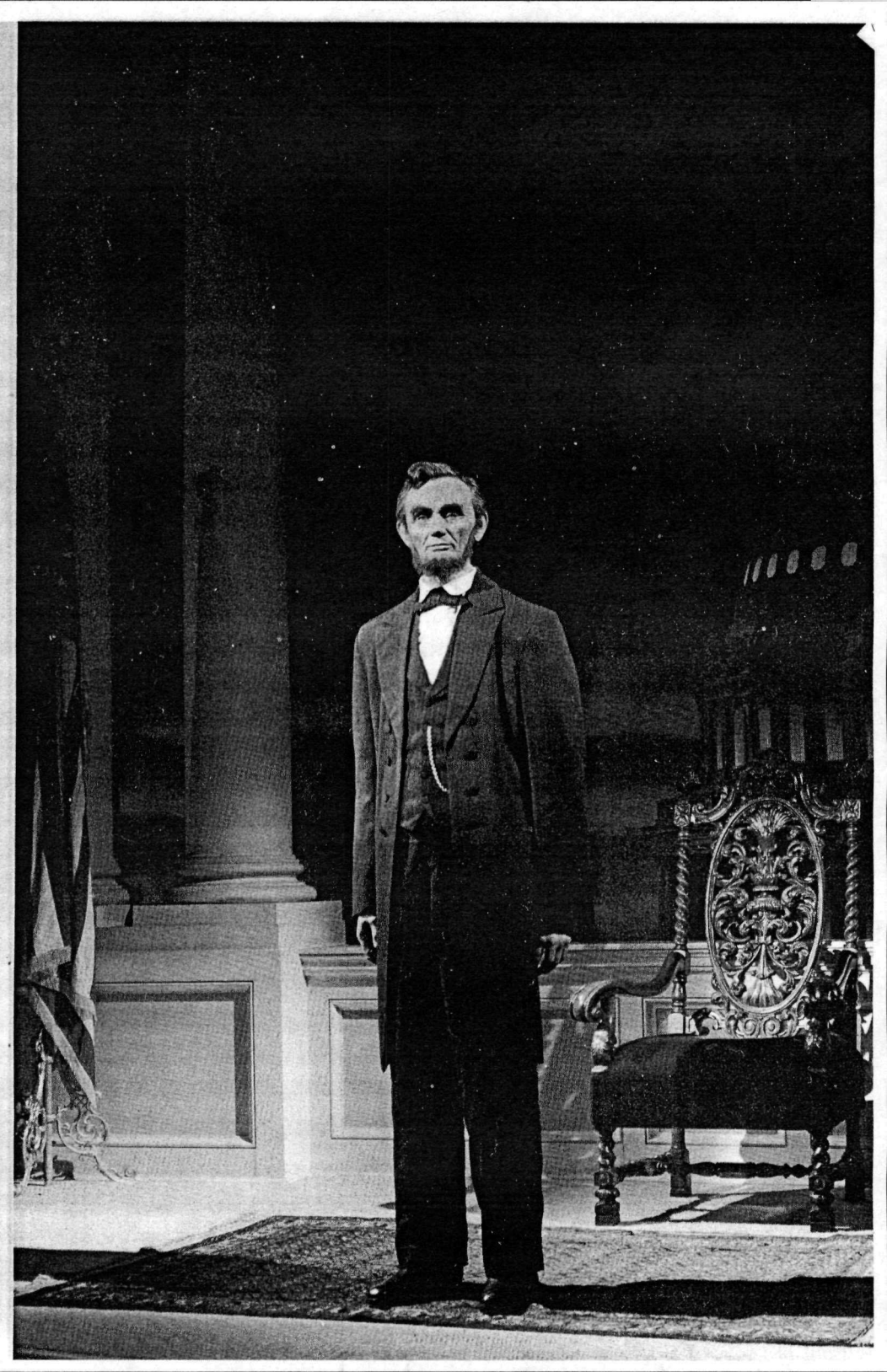
a mechanical Abe Lincoln looks very real as he responds to recorded control signals. Puppets and automatons, like television, are essentially frivolous—mainly for entertainment—but they have all stimulated technology; that is, in building them we have learned how to make artificial hands move deftly, how to control walking machines, and how to communicate with proficient machines over distances.

Sophisticated teleoperators did not begin to appear until the American atomic energy program began in the 1940s. The first big nuclear reactors put into operation at Hanford, Washington, produced prodigious quantities of radioactive materials that were subsequently processed chemically to remove plutonium for nuclear weapons. Never before in history had human beings had to handle such intensely radioactive materials.

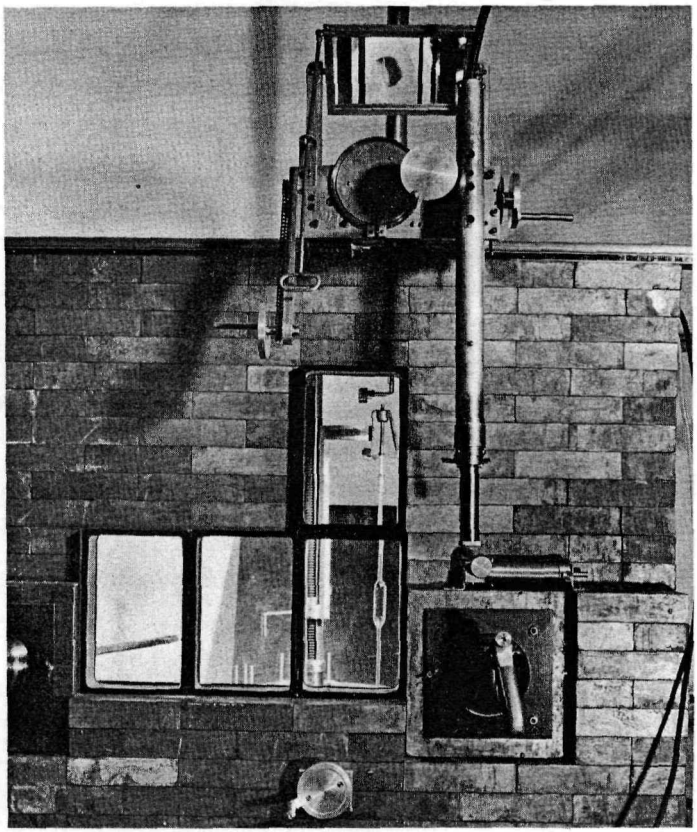
To protect themselves from the intense nuclear radiation, engineers erected thick radiation shields between themselves and the radioactive materials. But they had to find ways to manipulate chemical apparatus *through* the radiation shield. In effect, they had to build expendable (but dexterous) machines to work with the lethal chemicals.

The remote manipulations of retorts, chemical balances, and the other tools of chemical processing were far more challenging than holding red-hot horseshoes or retrieving packages of cereal. Nevertheless, the first manipulators built for working through the radiation shields were long tongs not much more sophisticated than those of the blacksmith. Often the tongs were mounted in a movable ball joint in the shield wall, which permitted the operator to swing the tongs around without exposing himself to radiation streaming through an

The mechanical Abraham Lincoln in Disneyland gives a 10-minute address compiled from six of Lincoln's speeches. The figure appears completely lifelike in every detail with coordination of speech, facial expressions, and body movements.



open hole in the shield. While operating the tongs, the operator looked through the shield with a periscope, an overhead mirror, or (in the modern hot cells) a thick window capable of stopping nuclear radiation but not light waves.



An early manipulator at Brookhaven National Laboratory. Motion was communicated over the lead brick wall by various mechanical linkages. Overhead mirrors were used in addition to the thick windows.

The First Unilateral and Bilateral Manipulators

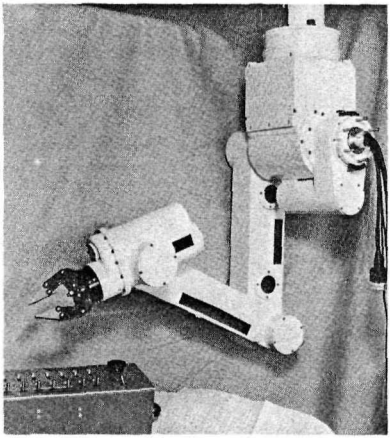
Something better than tongs was needed as radiochemical operations became more and more elaborate—pouring, stirring, weighing, assembling, drilling, grinding, etc. In this

search for better machines to help the hot cell operator project his manipulatory capabilities through the shielding wall, engineers at the AEC's Argonne National Laboratory, near Chicago, developed the first *unilateral* manipulators.

If you have ever tried to pick up a prize with one of those mechanical "hands" (or buckets) at an amusement park, you have operated a unilateral machine. There is no sense of touch or, as they say in the teleoperator field, no *force feedback.** An artificial arm with fingers that close through the action of a small electric motor is also a unilateral teleoperator. You can see what your artificial hand is doing but you cannot feel anything.

Despite the lack of feel, several important advantages are gained when electric motors are substituted for human muscles: (1) the mechanical arm and/or hand may be miles away from the operator (with a TV link to show the operator what he is doing); and (2) the arm-hand may be made much more powerful than those of the operator. Thus, distance and strength became the first two teleoperator attributes to

*Feedback is information sent back to the operator to help him operate the machine. It may be visual, audio, or data for any of the senses.



A typical switch-controlled electric unilateral manipulator. These are found in hot cells and various other industrial applications.

extend man's manipulatory capabilities beyond those nature gave him.

The first "bilateral" manipulators were devised a year later in 1948 by Ray Goertz and his Argonne group and John Payne at the General Electric Company. Bilateral teleoperators have a crude sense of touch; that is, when the mechanical fingers close on a glass beaker, the operator can feel the resistance of the glass wall to the pressure of the fingers.* Not only does the sense of touch, which is really force feedback, improve the deftness of the man-machine combination, but it also prevents the superhuman strength of the machine from breaking delicate objects.

The early bilateral manipulators operated via a system of metal tapes and cables that transmitted the motions of the operator's arms and hands to the mechanical counterparts in the hot cell. The motion of the tapes and cables was so nearly frictionless that the sense of touch was reflected back to the operator mechanically. Nevertheless, some friction did exist and the mechanical manipulators—often called "master-slaves"—lack the delicate sense of touch we have in real life. Working with a mechanical master-slave is rather like working with heavy gloves on. Despite this handicap, mechanical master-slaves have been built by the thousands for use in the nuclear industry, explosives plants, and other hazardous areas. They are the most common type of manipulator.

The word *feedback* was mentioned earlier in connection with the sense of touch. Whenever any kind of information is *fed back* to the operator of a machine, we enter the domain of *cybernetics*, a term describing the cooperative union of man and machine. Cybernetics evokes images of computers

*"Bilateral" in teleoperator parlance does not mean physical symmetry as it does in biology; the mechanical hand of the teleoperator may not look at all like the human hand that is controlling it.

and highly sophisticated man-machine systems; and it was in this direction that teleoperators next evolved.

Ray Goertz and his co-workers at Argonne applied the principles of cybernetics to manipulator design and in 1954 constructed the first electric master-slave. The cables and metal tapes connecting the master arms and hands to the slave counterparts were replaced by electric wires that carried control signals in one direction and force feedback signals in the other. When the operator used his hand to close the grips on the master, the action sent signals to a servomotor in the slave hand that closed its mechanical fingers at the same speed. From the technical standpoint, this was a momentous development.

Now, the bilateral teleoperator, like its unilateral cousin, could conquer distance with wires or radio signals. In principle, an earthbound scientist could pick up and examine a lunar rock via radio signals spanning 240,000 miles. But, of course, this was all happening in 1954, when sending machines or men to the moon was patently impossible. The important task at hand was the safe handling of radioactive materials.

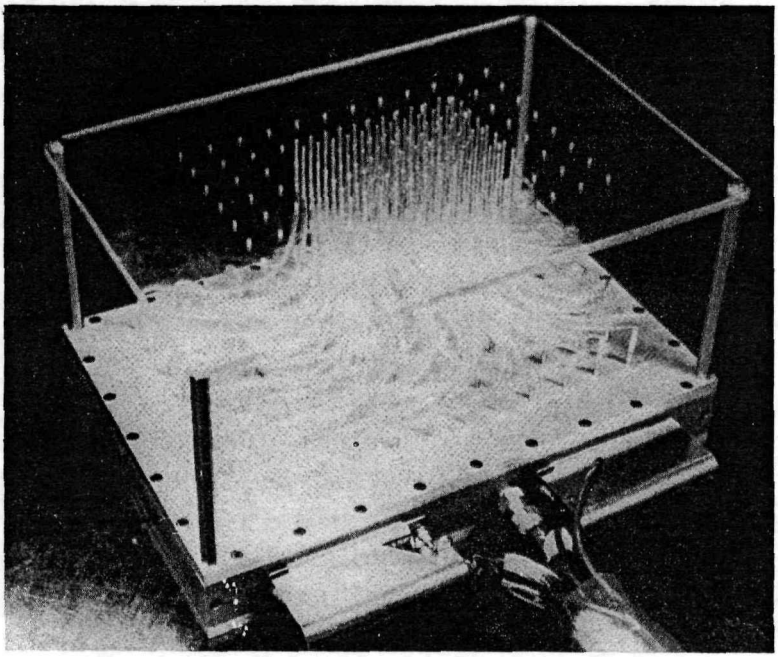
The Sense of Touch

There are really two kinds of feedback involving force and/or touch. The coarser of the two is simple force feedback, which indicates only a resistance to further movement. Force feedback in a teleoperator hand can be sensitive enough to warn the operator that he is about to break a fragile object, but it is not sensitive enough to tell him that the object is round or flat or rough or smooth. In other words, force feedback is not quite the same as the sense of touch; it is not what is called *tactual* (tactile) feedback. With tactual feedback, a blind person can become as adept at some manual tasks as a sighted person.

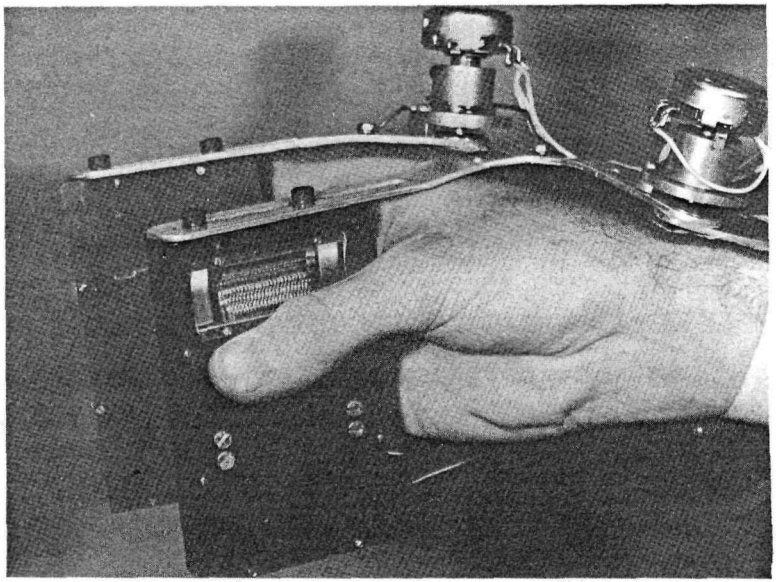
Our sense of touch comes from thousands of nerve endings in the fingertips. To reproduce even a coarse sense of touch, the teleoperator master fingers would require many stimulating devices each actuated by pin-sized sensors in the slave's fingertip. Each tiny sensor (perhaps an electromagnetic solenoid) would have to be connected to a similar feedback stimulator in the master finger control.

The remarkable thing is that very successful touch sensors have been built not primarily for teleoperators but rather for aiding the blind. The technology has also been successfully applied to teleoperators.

One of the problems faced by blind people is the scarcity of reading material published in Braille. James C. Bliss and his colleagues at the Stanford Research Institute have devised a



An 8 × 12 array of air-jet tactual stimulators. The active area of the array is fingertip size.



A teleoperator master hand incorporating piezoelectric vibrators that convey a sense of touch from piezoelectric sensors located on the slave hand. There are 144 vibrators in the 6 × 24 array for the thumb and an identical array in back for the index finger. The sensor arrays on the slave hand are arranged in the same way.

reading machine that translates printed letters (or anything printed or drawn) into mechanical sensations on the finger, which anyone, whether blind or not, can easily interpret as letters.

The sensation of touch is created by a closely packed array of air jets. As an optical sensor moves across the letters on a printed page, tiny light-sensitive cells send open or close signals to corresponding, electrically operated air jet valves. The machine interprets black areas as signals to open air jet valves. Thus, when the letter A is under the optical sensor, those air jets arranged in the shape of an A stimulate the reader's finger. The overall sensation is similar to that felt when running one's fingers over raised lettering.

Bliss has also substituted an array of tiny piezoelectric crystals for the optical sensor. A piezoelectric crystal—common in phonograph pickups—generates an electrical signal when pressure is applied to it. With signals from the crystal array actuating the array of air jets, the sensations of roughness and shape can be transmitted electrically. Present-day teleoperators need such sophisticated touch sensors, but one can see how they could be applied one day to the assembly of electronic parts in a vacuum or even, in the distant future, to manipulations as delicate as remote surgery.

The Importance of Seeing What You Are Doing

Blind people have an uncanny ability to manipulate objects, assembling relatively complicated objects through the sense of touch alone. The average person cannot do this. Without sight he cannot be proficient with the best electric master-slave manipulator because its force feedback cannot yet equal the sensitive nerve endings on his fingertips.

The manipulator operator must be able to see what he is doing, and so visual feedback is essential. Hot cells and deep-sea submersibles usually have windows so that the operator can see into the hostile environment; but of course there is no window to the moon except through television.

Assume that you were a geologist and wished to explore the moon from earth by means of a mobile teleoperator sent there by rocket. Or suppose you were a surgeon later in this century and were preparing to perform remotely a delicate operation on a patient on the other side of the world. In both cases, you would want to see things as if you were actually at the scene of action; you would want to be able to project yourself as completely as possible to the moon or into the distant operating room.

The operator's "sense of presence" can be greatly improved by fitting him with a device that permits him to see what is actually happening wherever he turns his head. The average TV camera cannot do this.

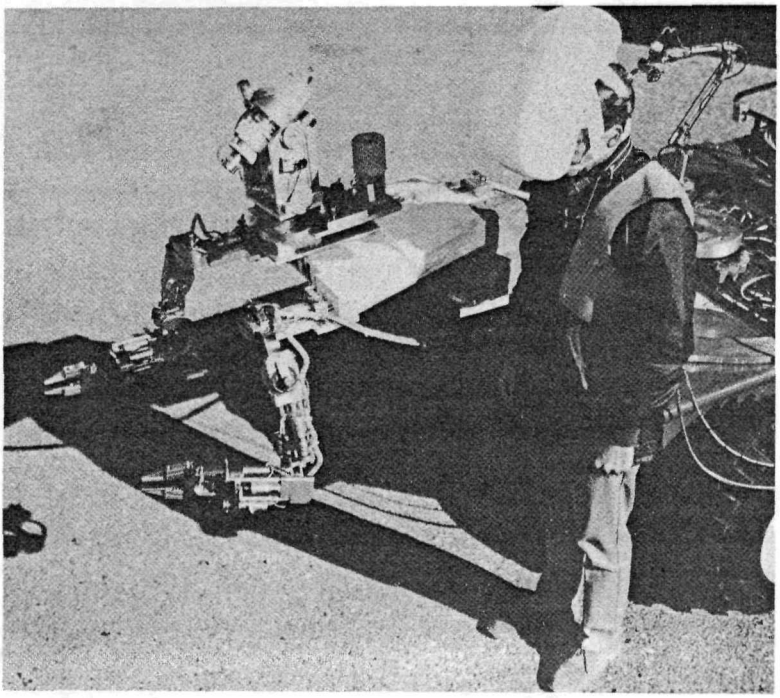
However, if a special helmet is placed upon the operator's head so that his head motions are turned into signals that point the TV camera in the direction his head is turned, we can make a distant scene a lot more realistic. On a small screen directly in front of his eyes, he would see whatever the distant TV camera relayed back. The surgeon could, for example, glance up and check instruments monitoring his patient's vital functions. To this end (but without thoughts of future surgery) a group of engineers at the Philco Corporation, including William E. Bradley and Steven Moulton, in 1958 built a miniature head-mounted TV set that enabled the wearer to project himself effectively into a distant place.

By 1965 Ray Goertz at Argonne had added the head-controlled TV concept to the Argonne electric master-slave. It is an eerie feeling to wear the Argonne TV head control and insert one's hand into the glove-like master-slave controls and manipulate objects at a distance. One is transported via cybernetics 20 feet, 100 miles, to the bottom of the sea, to wherever the slave portion of the teleoperator is located.

In fact, one can conceive of future teleoperators reproducing other attributes of the distant environment—sound and smell, for example—everything except the hazards of the environment. Why travel when you can put yourself anywhere on earth (or the universe) electronically?

Power to the People

Thus far, the conquests of distance and hostile environments have been the primary goals of teleoperator develop-



A self-propelled anthropomorphic manipulator (Sam) was built for a nuclear rocket program. It is also being used by the Navy for bomb disposal operations. The TV camera is controlled by the operator's head. There is a television screen under the face mask.

ment. But who wouldn't like to be able to lift a ton or toss logs around like matchsticks? After all, we all get a vicarious thrill out of Superman's comic strip episodes.

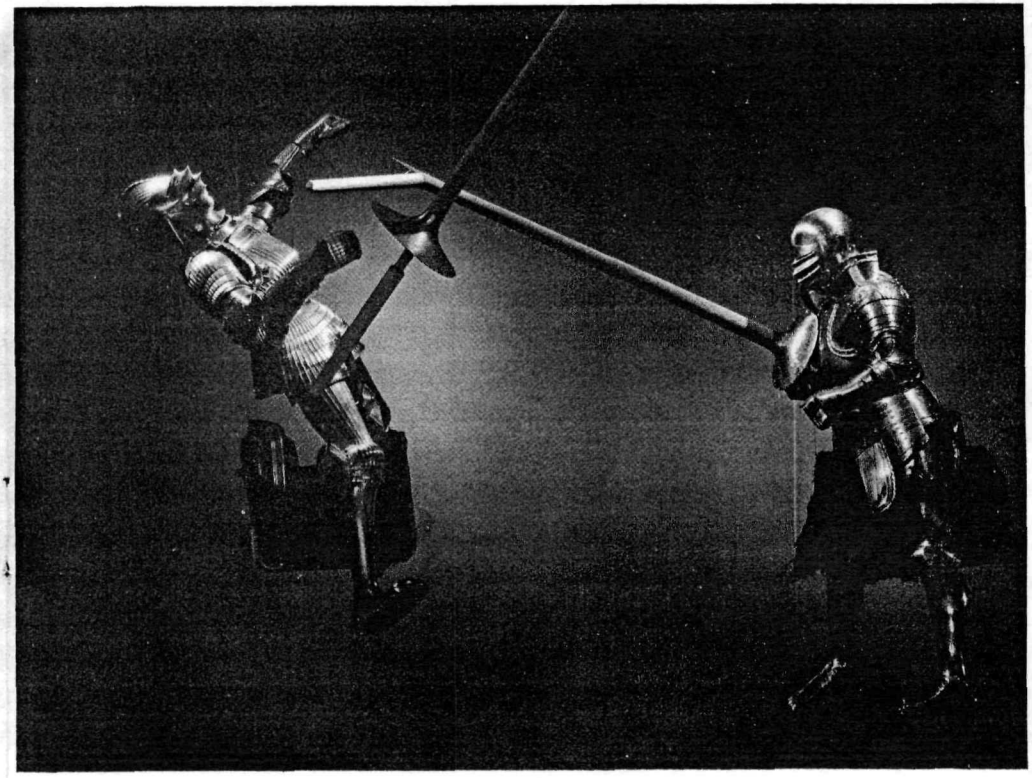
The man-amplifier concept, like so many other elements of technology, originated with the military. In 1964 Neil J. Mizen and his colleagues at the Cornell Aeronautical Laboratory reported their work on a "wearable, full-scale, exoskeletal structure". The medieval knight's suit of armor was an exoskeleton which, like the beetle's carapace, protected the wearer from hostile missiles. If the suit of armor is made thicker to ward off modern small arms fire and has servomotors at its joints, you have a "super-soldier".

The entire body of the operator of the man amplifier fits inside the machine just as the hand and head fit inside the

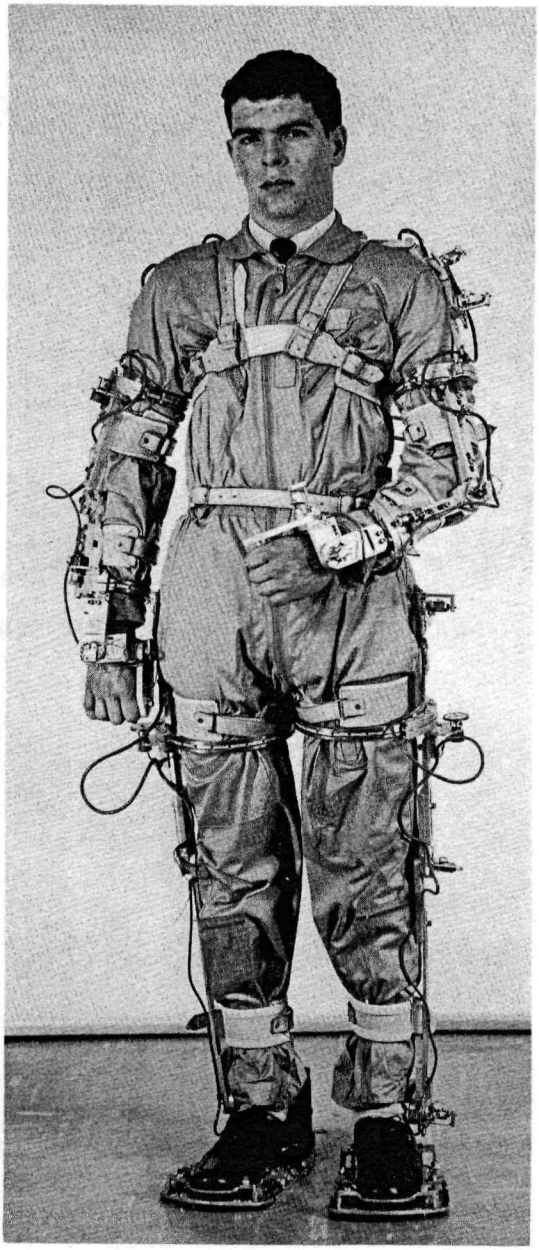
controls of the Argonne master-slave manipulator with its head-controlled TV, except that now the entire body is duplicated by the slave portion of the machine. In the late 1960s, the Hardiman man-amplifier concept mentioned earlier was developed by General Electric under a Department of Defense contract for the dexterous handling of heavy loads at military installations.

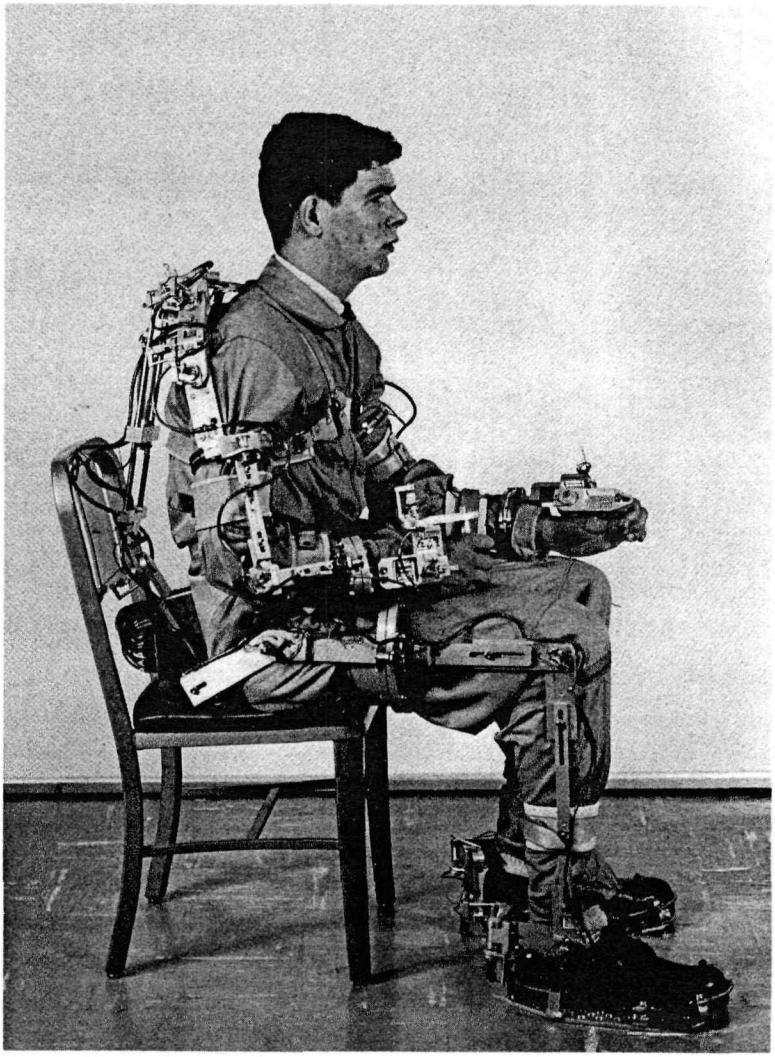
Giving the Brain a Rest

The final development of historical import involves the digital computer—that omnipresent consumer of punched



The medieval knight's suit of armor was a protective exoskeleton.





An exoskeleton built by Cornell Aeronautical Laboratory. If powerful motors were placed at the joints, an exoskeleton becomes a man amplifier. Or, by mounting servos at the joints, the exoskeleton can be used to control man-like teleoperators, such as those shown in the figure on page 35.

cards. Earlier, it was emphasized that the teleoperator is a man-machine system that relies upon the human operator to do the thinking for both man *and* machine. It is time to hedge a little because there are three circumstances when a good computer can be of substantial help to a teleoperator:

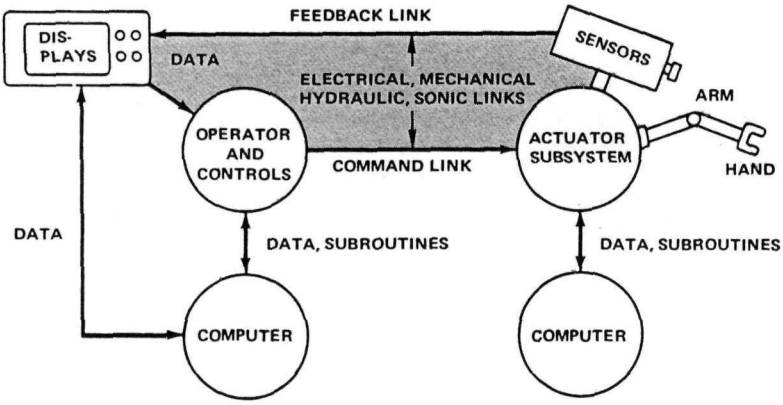
1. When tasks are routine and there is no need to burden the human operator with them.

2. When tasks are too complex for man to perform unaided; for example, the assembly of objects in a known but unfamiliar environment, such as the assembly of a space station in orbit under zero-gravity conditions, where the laws of motion are known but human experience with earth's gravity is not always a good guide. A computer can learn these new laws and perform the more routine motions.

3. When the teleoperator slave is located so far away that radio signals carrying visual and force feedback signals take more than a few tenths of a second to travel back to the operator. This time delay is extremely disconcerting to a human operator and he cannot perform well without the assistance of a computer. Time-delay problems arise with space operations on the moon and planets and in undersea work where sound waves (which are much slower than radio waves) carry the feedback information.*

In all three circumstances listed above, the general purpose digital computer is called upon to aid the human operator in what is called *supervisory control.* In other words, the human operator gives generalized instructions to the computer, such as "Bolt object A to object B"; he then relinquishes control to the computer until the task is completed. He maintains the

*NASA began sponsoring time delay studies in the early 1960s, first at Stanford University and later with an M.I.T. group under Thomas B. Sheridan.

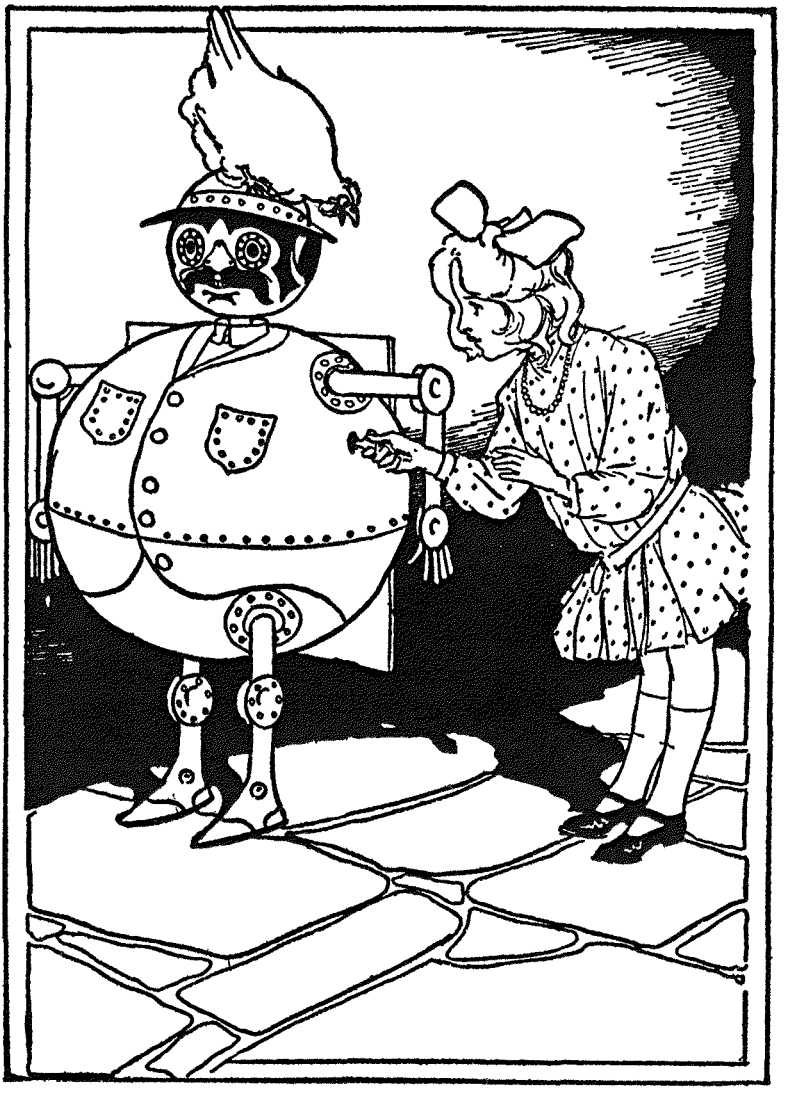


The teleoperator control loop (shaded). Control signals move from the operator to the actuator subsystem. Feedback returns to the operator where it is displayed to help him decide future actions. Computers may help generate displays and, in a supervisory capacity, actually control the teleoperator.

position of supervisor, watching the operations, and stopping them if the action goes awry.

The computer may also be called upon to predict the future in situations where excessive time delay exists. The predictions are based upon physical laws, of course, and they create an artificial picture of events just far enough into the future to cancel out the effects of time delay. Thus, the operator thinks he is working in *real time*, that is, he "thinks" there is no time delay.

This is called a *predictive display* and is a little like gazing into a crystal ball. Although teleoperators are definitely not artificially intelligent automata, the use of the computer in supervisory control is a big step in the direction of intelligent robots.



Tik-tok was the most famous thinking machine in the land of Oz.

UNITING MAN AND MACHINE

Teleoperators have split personalities. On one hand, we have the human operator, possessing an excellent brain, good eyes, and highly skillful hands; yet he has his frailties. On the other hand, there is the machine, which is rugged, impervious to many environmental forces, and yet rather inflexible and unquestionably stupid in its present stage of development. How do we mate these two disparate entities—flesh and blood with metal and plastic? A flip answer would be, "With difficulty", for man-machine integration is a great engineering challenge. However, some better answers are possible.

First, a model of the teleoperator will help focus our thinking. The human interacts with the machine through *controls* of various types, which send commands to his machine partner, wherever it may be, through a *communication link*. The commands received by the machine are turned into specific manipulatory or pedipulatory actions by *actuators* or *effectors*; that is, the motors, solenoids (electromagnets) or hydraulic pistons that bring the machine to life.

On the machine side, there will be *sensors* such as TV, which dispatch information about what the machine is doing back to the operator through the communication link. Because beeps and electrical pulses have little meaning in themselves to the operator, electronic equipment generates a *display* that interprets machine actions in human terms, such as a TV picture of the action.

Thus man and machine, though they may be inches or thousands of miles apart, are linked via wires, or even lasers. The better the design of the teleoperator, the more satisfactory the symbiosis* will be regardless of distance.

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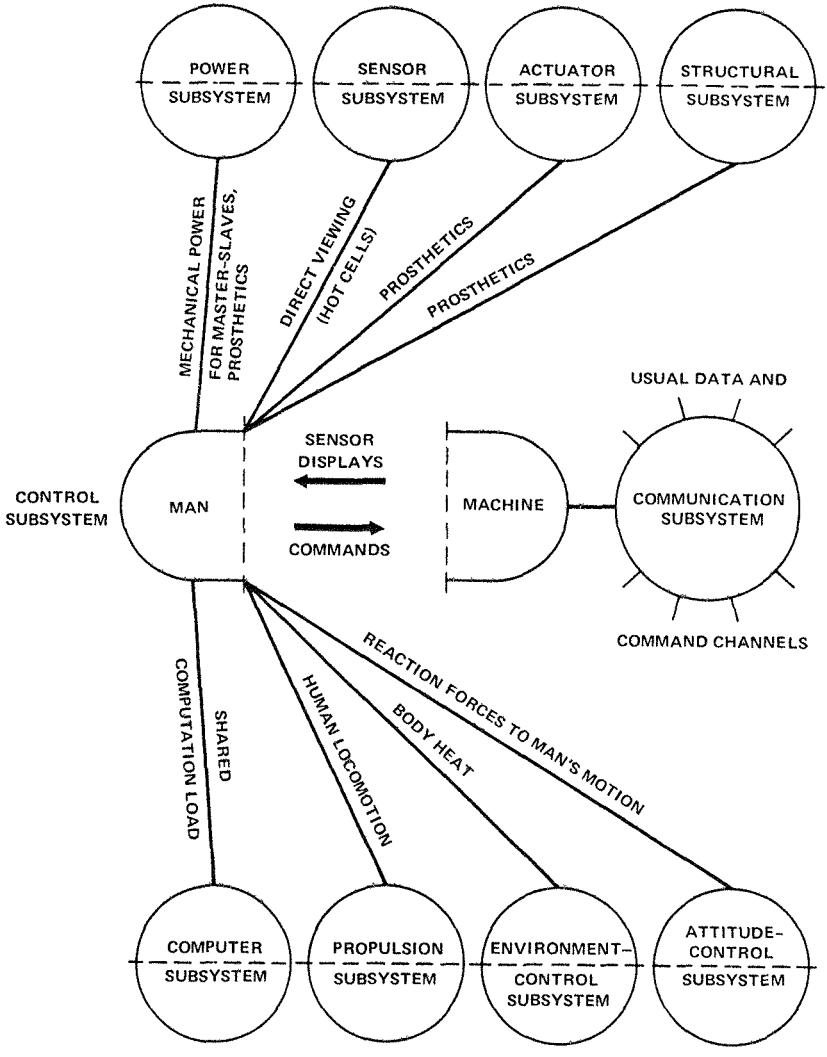
*Symbiosis is the beneficial union of man and machine or, more correctly, of two life forms.



Ten teleoperator subsystems are shown in this drawing. The heavy radiating lines show direct interactions between the man and the machine. Most control information and sensory data are transmitted through the communication subsystem.

It is customary to call a teleoperator a "system" or, more specifically, a man-machine system. Each of the five major elements of the system listed above is called a "subsystem". Control and display subsystems are on one side of the man-machine interface, actuator and sensor subsystems are on the other. All of this is linked by a common communication subsystem. However, a good engineer realizes that he must analyze thoroughly a new system concept to see if he has thought of all the pieces of the puzzle.

A little reflection about teleoperators and the things they do proves that a number of lesser but still critical puzzle pieces (subsystems) have been left out. For example, the teleoperator actuators do physical work when they move objects. Where does the energy come from? Obviously, a *power subsystem* is essential. Further, a *propulsion subsystem* is needed to move the teleoperator from place to place in many applications.

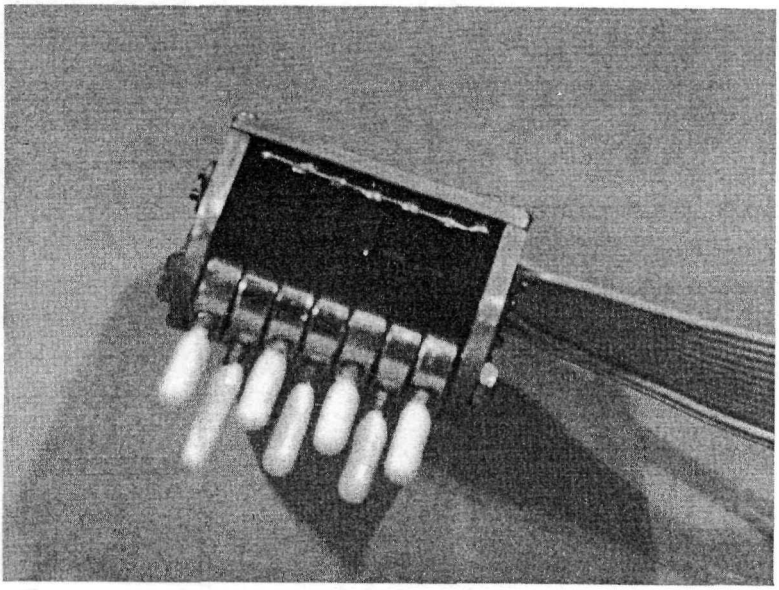
In spacecraft, under the sea, and in other hazardous environments, the machine itself must be protected by an *environment control subsystem.* The existence of this subsystem is, of course, an admission that machines cannot prosper in all environments, although they can survive in them a lot longer than a human. If the teleoperator is mounted on a vehicle, an *attitude-control subsystem* may have to be added to keep the machine properly oriented in space or ocean. Finally, both the operator and the machine may need *computers.* A computer subsystem can generate displays and help the operator make decisions; the machine may need computer help in situations where the operator temporarily turns control over to it.

In the design of teleoperators, the question of *anthropomorphism* crops up frequently. For example, your automobile is decidedly not very anthropomorphic or man-like. It has four "feet", it rolls instead of walking, and it cannot

manipulate anything. Despite the automobile's nonhuman characteristics, men learn to drive it with great skill. Man-machine integration is good. The situation should be different with teleoperators where highly specific human traits (particularly hand dexterity) are being transferred across distance and through barriers. How proficient would a teleoperator be if the machine had only a two-fingered hand? The answer is, "Surprisingly proficient".

In fact, most master-slave manipulators have only two fingers on each hand. It turns out that the human being is a surprisingly pliable creature and can adjust himself to many non-anthropomorphic situations very well. For example, some disabled persons control their electrically powered artificial limbs with simple tongue switches.

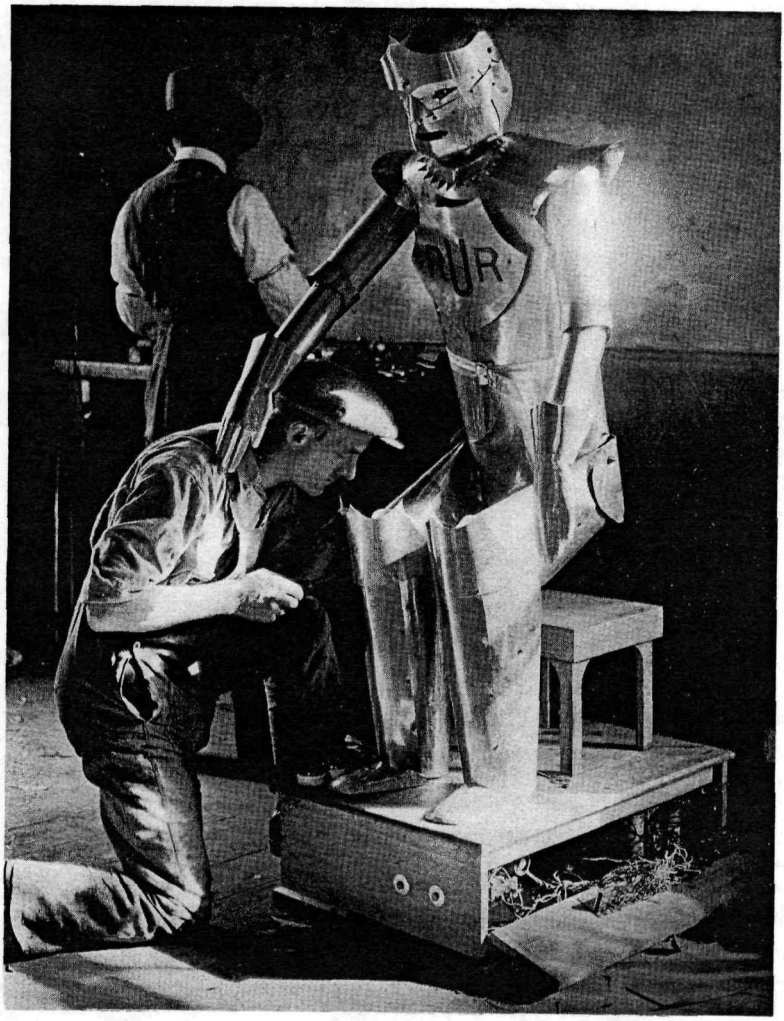
A person can even learn to cope with an upside-down world when given special glasses that invert the scenery



A tongue switch used by severely handicapped persons. Each toggle is a three-way switch controlling a degree of freedom in an artificial limb.

around him. But there are limits. Men cope best in a familiar world, especially where human skills requiring great concentration are involved. For this reason, teleoperators are generally made highly anthropomorphic. Manipulator hands have opposing "fingers and thumbs", look like human hands, and the controls fit right over the operator's hand.

When the operator's hand moves to the right, so does the machine hand; it would be most disconcerting otherwise. It is reassuring to watch a television screen and see your motions duplicated faithfully. Anthropomorphism definitely improves an operator's dexterity. The moral of this discussion is that teleoperators should be man-like where possible, but if a special task requires a nonhuman motion, such as infinite wrist rotation (useful in putting nuts on bolts), the human operator can find a way to control the motion. Man is generalized and flexible, but the machine is not.



This robot was built in the 1930s by a Captain Richards in England. It could speak, shake hands, and sit down. R.U.R. is the title of a 1921 play by Karl Capek, a Czechoslovakian playwright, and stands for Rossum's Universal Robots. Capek's play introduced the word robot into the English language.

TELEOPERATOR APPLICATIONS

The overwhelming majority of present-day teleoperators see service in radioactive hot cells; there are also a few on research submersibles, ordnance disposal systems, and unmanned deep-ocean exploration vehicles. All the talk in the preceding pages about planet-exploring machines, urban servants, and long-distance surgery is really wishful thinking. Nevertheless, such hopes for the future frequently turn into reality. Therefore, let us take a bold optimistic look at today's teleoperators and try to guess what they might do tomorrow.

Machines Rather Than Men

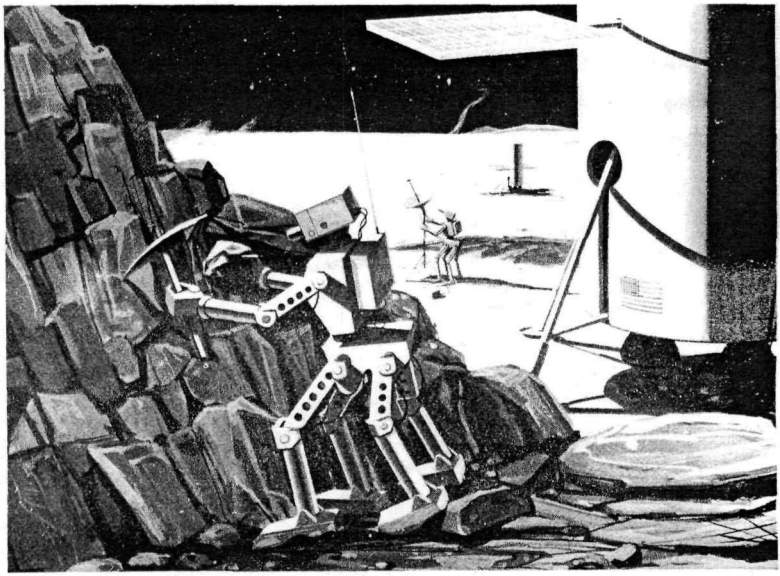
Outer space is one of the few remaining great frontiers. Somewhere among the planets that circle the sun—and undoubtedly other stars, too—reside some of the answers to the riddle of our existence. Eventually, we shall wish to explore beyond the moon in person, but until we can mount such prodigious manned expeditions, teleoperators will make admirable inexpensive and expendable precursors.

A primitive type of teleoperator actually did precede the astronauts to the moon. Some of the Surveyor lunar landers that settled softly onto the moon's surface during the 1965–1968 period carried shovel-like samplers that were primitive teleoperators. Early in the space program there was fear that spacecraft would founder in lunar dust. Therefore, the scoop-like manipulator shown in the figure was included in some of the Surveyor payloads. The Surveyor samplers dug trenches to test the texture and hardness of the lunar soil. Rock samples were also tested for strength.

From the standpoint of a manipulatory tool, the Surveyor sampler's greatest moment came when, on one landing, an experiment refused to deploy properly. By command

from earth the sampler was brought around and jarred the experiment loose so that its sensor unreeled and finally came to rest on the lunar soil. The exploits of Russia's Lunakod have demonstrated further the great value of sophisticated machines in exploring the moon and planets by remote control.

The Surveyor sampler, controlled by radio from earth, dug trenches on the moon and helped deploy a scientific experiment. This picture was taken during a test on earth.



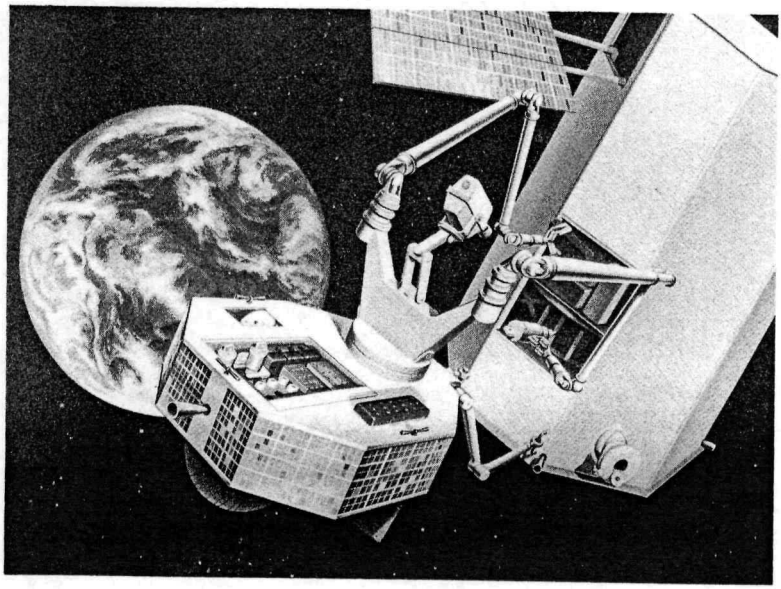
Remotely controlled robot-like teleoperators with TV camera heads are technically feasible and could be of great value in unmanned space exploration.

From such simple beginnings, teleoperators will graduate to more challenging roles in the exploration of the planets. The robot-like teleoperator in the figure, although looking like something out of an ancient science fiction movie, is nevertheless a practical rendering of the teleoperator concept. Some human operator on earth must go through the same actions as the metallic "creature" in the figure. (Of course, mechanical prospectors need not look quite so human to be effective.) The immense cost of manned space exploration has made teleoperators and "robotics" an important NASA objective.

Closer to earth, teleoperators are useful in orbital operations for two reasons:

1. The repair and maintenance of expensive unmanned satellites is economically desirable. NASA's Orbiting Astro-

nomical Observatories, for example, cost over $100 million apiece to build and launch. When electronic parts fail or when an experiment needs adjusting, a maneuverable, manipulator-carrying satellite could make the necessary changes under direct control from earth or a manned space station.

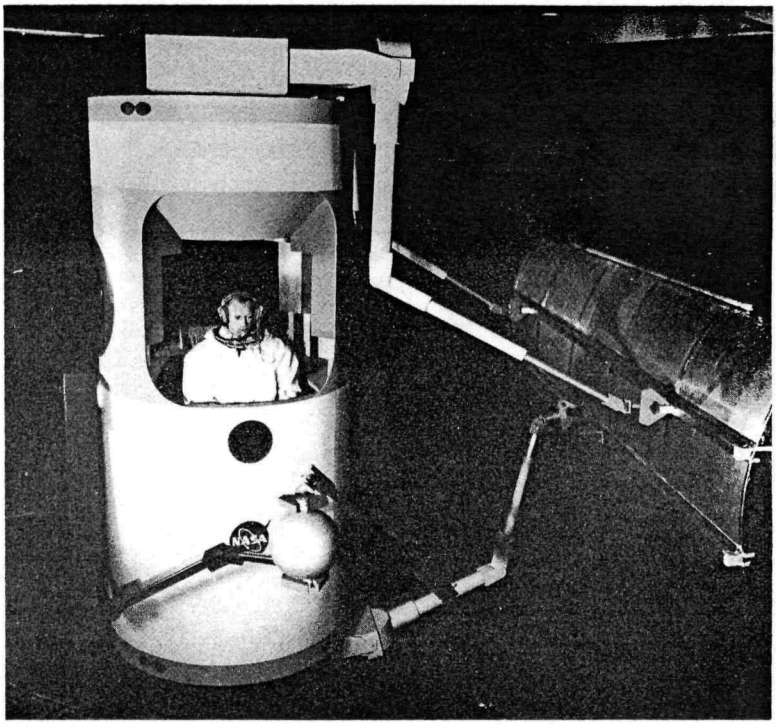


Conceptual drawing of a teleoperator repair and maintenance satellite. The large satellite being serviced is an Orbiting Astronomical Observatory.

2. Space qualifies as a hostile environment and rather than subject astronauts to unnecessary EVAs (Extra-Vehicular Activities) teleoperators can help assemble orbital space stations and aid in cargo transfer.

Probing Inner Space

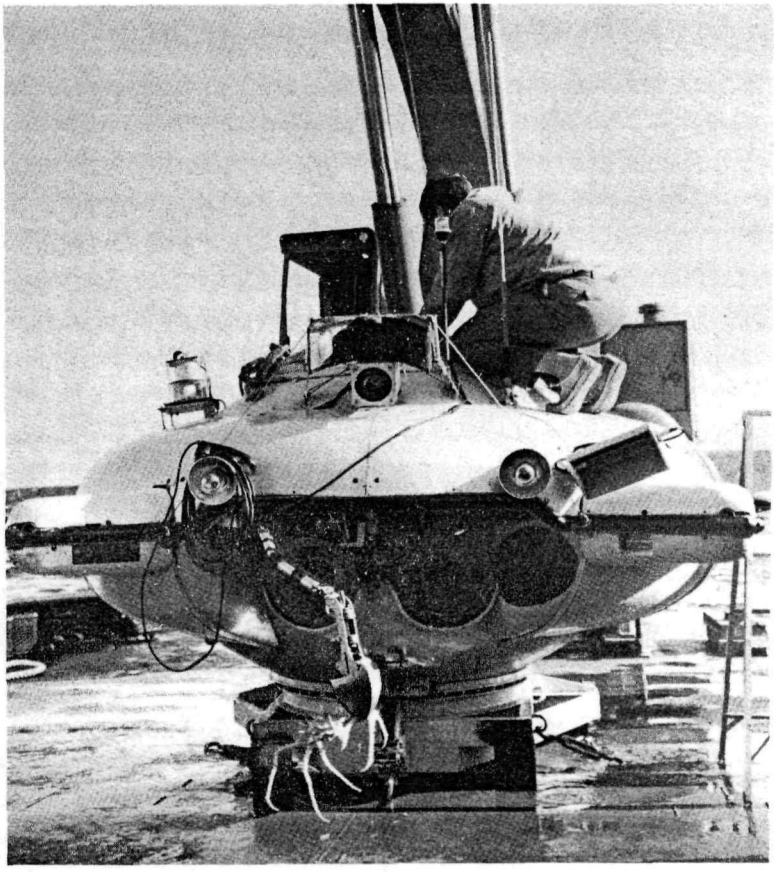
The sea covers seven-tenths of the earth's surface and thus obscures much of the geological and (to a lesser extent) archeological records of the past. Dredging up this evidence



Mock-up of a Space Taxi. The complete taxi would have two "working" arms for maintenance and repair and three "docking" arms for facilitating rendezvous in orbit.

from surface ships is at best a hit-or-miss proposition. Small research submersibles (manned or unmanned) with manipulator arms are much more effective. Dozens of these craft have already been built and are now busy exploring the continental shelves. The submersible *Ashera* was built specially for the investigation of human settlements built millenia ago when the sea level was much lower. Other submersibles use their manipulators to collect rocks and sea-bottom samples.

Quite possibly, what we find on the seabeds will be just as important in unravelling the history of the earth and man as the close examination of the rocks and soil of Mars.



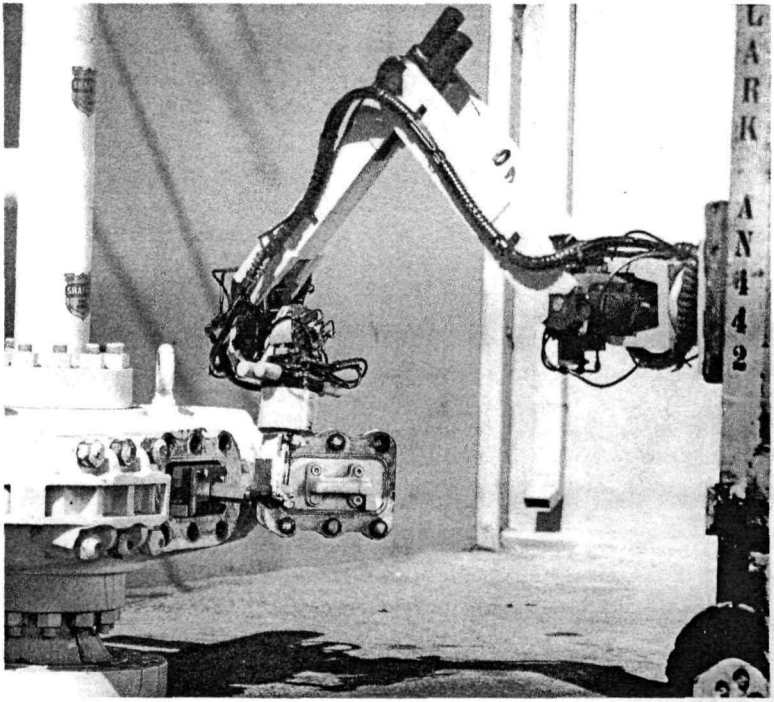
This diving saucer has a hydraulic manipulator, called a "clamshell grab". The manipulator hand is holding a spider crab.

The mineral riches of the sea also require that men learn to work on the sea floor. American oil companies, for example, have built submersibles to help them tap offshore oil deposits with less risk to divers who cannot work efficiently in the cold murky waters several hundred feet down. In addition, the ability to work more effectively underwater should help prevent oil leaks and other "plumbing" failures that now plague offshore oil operations and damage shoreline ecologies.

Working with Radiation (or in Spite of It)

The nuclear industry has always been the biggest user of teleoperators. In fact, nuclear-electric power and the widespread use of radioisotopes in industry and medicine would be severely hampered without manipulators for handling radioactive materials.

As mentioned earlier, the development of manipulators was spurred by the need to work with the radioactive materials produced in the manufacture of nuclear weapons. It became apparent during the 1940s that many of the radioisotopes that were being discarded into underground waste storage tanks could be a great boon to industry and



In this test, a hydraulic unilateral manipulator is replacing a blow-out preventer ram in a simulated off-shore oil well. This task is difficult and dangerous for divers in deep water.

medicine. Furthermore, the new nuclear reactors being built could also manufacture radioisotopes specifically tailored to commercial and medical needs. Engineers, scientists, and doctors could, in principle, order radiation sources and radioactively tagged chemicals and medicines just like they order any other commercial product.

The "catalog stage" in the application of radioisotopes has arrived. Many thousands of radioactively tagged compounds are available to hospitals, universities, the chemical industry, pollution-control agencies, and anyone else with a legitimate need. All this, however, could not have happened without the availability of manipulators to handle the radioactive materials as they come from reactors and in the manufacture of the required compounds.

As nuclear power assumes more and more of the burden of generating the world's electricity, more and more manipulators will be bought for the reprocessing of fuel that has been partially "burnt" in power reactors. Right now, we fuel nuclear reactors mainly with uranium directly from mines. This uranium is not radioactive enough to require the use of manipulators in manufacturing reactor fuel elements. As the so-called "breeder reactors" come into operation within the next decade, plutonium will become the predominant nuclear fuel.* Plutonium, however, is more highly radioactive than uranium, and it will necessitate the greater use of manipulators in fuel manufacture.

Nuclear accidents are very rare. During the nearly three decades of the atomic era only 5 people have been killed in nuclear accidents—an enviable safety record in any industry.

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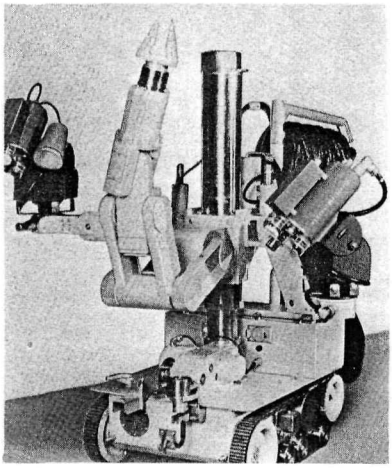
*Breeder reactors produce more nuclear fuel than they consume. For example, uranium-238, the most abundant uranium isotope, is *not* readily fissioned in reactors. A breeder reactor can convert uranium-238 into plutonium-239, which *is* easily fissioned and therefore a good reactor fuel. See *Breeder Reactors*, another booklet in this series.

However, accidents do occur and one must be ready for them. When a radioactive chemical is spilled or when a hospital technician inadvertently drops a radioactive source during cancer therapy, the area is quickly evacuated so that no one is exposed to a serious radiation dose. Sometimes, experts can rush into the area and clean up the spill or recover the capsule so quickly that no one is exposed to a harmful dose of radiation.

If the situation is too risky for a human, a mobile teleoperator can be sent in. A number of manipulator-carrying vehicles have been built. Directed by an operator from a safe distance—or through a TV camera on the vehicle—the teleoperator can move into the area and safely dispose of any dangerously radioactive materials.



The PaR-1 mobile manipulator. The vehicle and the manipulator arm are powered and controlled by cable. The manipulator arm and the two TV cameras are mounted on articulated booms. The height of the central support tube is 68 inches. The PaR-1 has been used in nuclear emergencies.

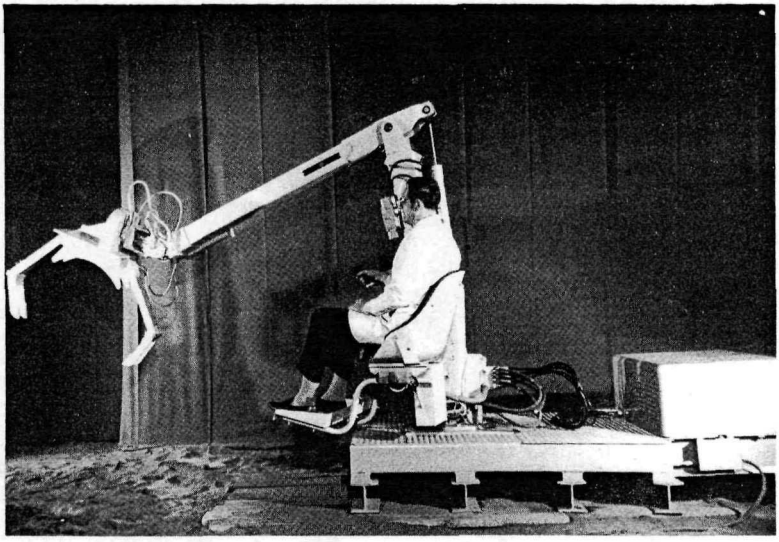
Teleoperators in Other Industries

Hot steel forgings, experimental explosives, and even some biological materials are too dangerous to handle without the help of special machines. In addition, certain work areas, such as mines and industrial environments filled with toxic gases or under high vacuum, are unsafe for

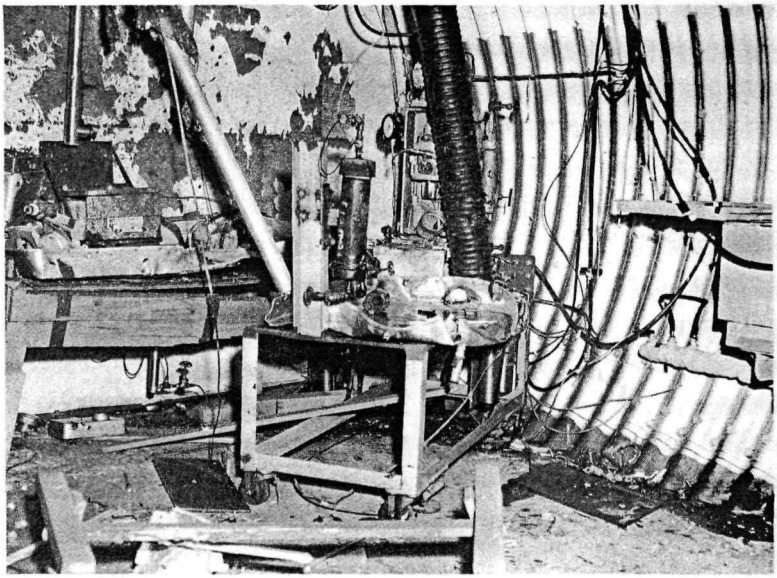
humans. When deft manipulation is required in such areas, manipulators should be considered. The cost of installing manipulators is customarily compared with the costs of doing the same task another way.

If toxic materials are being employed in an industrial process, for example, it may be cheaper to shut the facility down temporarily and permit men to enter to make adjustments rather than use teleoperators. Teleoperators have to pay for themselves in industry, and they are doing just that in some factories.

One of the most dangerous occupations in the world is that of mining. Teleoperators are not employed presently in operations. It is only a question of time, though, before mining is completely automated and controlled from the surface or another relatively safe area. Already the coal miner with his headlamp and pickax has been replaced in many mines by machines that cut away at the coal seams and automatically convey the product to waiting coal cars.



A Man-Mate manipulator used for handling heavy home appliances in warehouses and shipping areas.



Manipulators are applied to many industrial tasks involving the handling of hazardous materials. In this devastated laboratory, a mechanical master-slave was manipulating a beaker carrying 1 pound of high explosive. The protected operator did not even feel the shock.

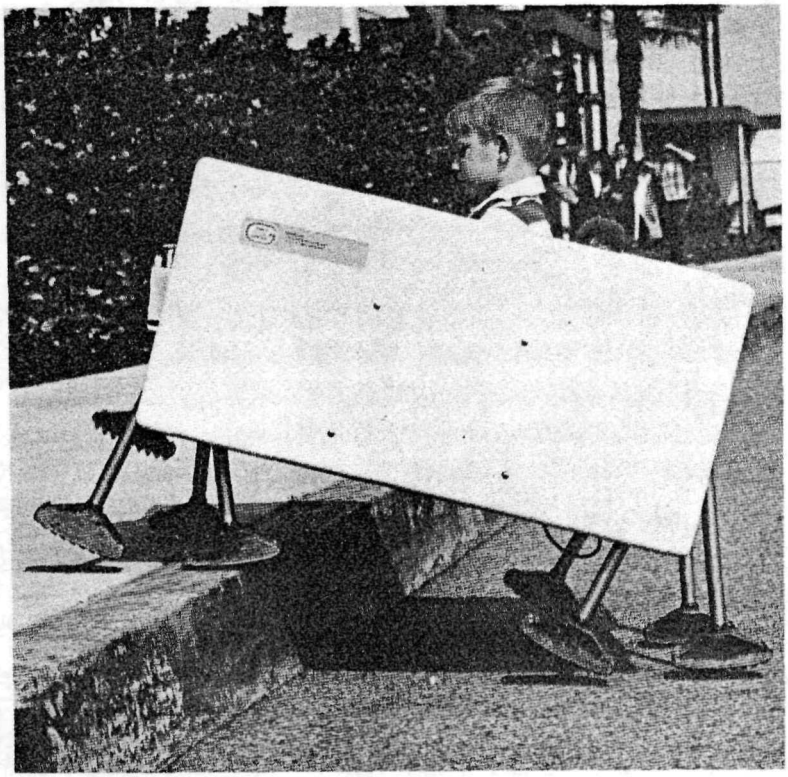
Men still run the machines, however, and there are other operations, such as blasting, that require the manipulatory skills of men. In principle, teleoperators can take over these dangerous tasks in our mines and other tunnelling operations. Teleoperators could be made so rugged that the placement and detonation of explosive charges in tunnelling could be made nearly continuous rather than the time-consuming sequence of set charges, retreat, detonate, move in, and clear out debris.

Walking Machines

Modern man moves mainly on wheels. Except for a few dune buggies, snowmobiles, and Army tanks, most modern vehicles are helpless without smooth, well-maintained roads.

Animals have solved the problem of off-the-road locomotion with their feet. Machines can do the same at some cost in complexity.

Crude walking machines have been built—mainly as toys—for hundreds of years. Even Abraham Lincoln was awarded a patent for a device similar to a walking machine for lifting ships over shoals. During the space program, small walking machines were proposed for carrying men and instruments over the lunar surface. One of these was actually



The Walking Wheelchair is a preprogrammed machine built for lunar exploration and then converted to terrestrial use. The operator can control only the direction of motion. This wheelchair is being evaluated as a special means of locomotion for multiple amputee children and others who cannot use ordinary wheelchairs.

built by Space-General Corporation. This machine was also tested as a "Walking Wheelchair" capable of negotiating curbs and other obstacles that would halt an ordinary wheelchair.

The most ambitious effort to build walking machines is military in nature. With support from the Department of Defense, General Electric is building the Walking Truck. The objective of this vehicle is the transport of men and material over terrain too rough for ordinary wheeled and tracked vehicles.

Whereas the Space-General Walking Wheelchair is preprogrammed in the sense that the legs always go through the same sequence of actions, the operator exercises direct control of the legs of the Walking Truck. The Truck's legs are "slaved" to the arms and legs of the operator. Force feedback is present and this makes the Walking Truck a bilateral teleoperator.

In the Service of Man

There are many dirty, demeaning jobs that men still do—ditch-digging, garbage handling, mind-dulling assembly-line work, and the like. However, the practicality of man amplifiers and, even more appropriately, man-like teleoperators controlled from afar, means that eventually these tasks will also be done by machines.

It may be that dullness and dirtiness are more deadly to human well-being than the so-called hostile environments discussed earlier. Teleoperators can tackle this class of tasks in two ways. First, the man can be physically removed from noxious surroundings and accomplish the task remotely from a comfortable control station. He would be in the control loop in this case. Or, second, the teleoperator could be "led through" the required task once by a human, during which all the necessary motions would be recorded. From then on, the teleoperator would do the task automatically as directed

by the recorded program. This is already done on industrial assembly lines with some simple part-handling machines.

With man-simulating teleoperators, the range of tasks could be expanded greatly. For example, one operator could easily supervise a dozen garbage-collecting teleoperators moving their stilted, preprogrammed ways down the back alleys of cities.

Man-like teleoperators are also expendable in emergencies. They could fight fires and rescue people in burning buildings; they could dislodge criminals barricaded in houses; they could take man's place wherever and whenever the environment becomes dangerous, disagreeable, or even merely boring.

The first machines built to emulate men were built for the purpose of entertainment. They were make-believe men operated by puppet strings or the levers of Von Hempelen's chess-playing Turk. Down through the centuries teleoperators have shielded men from dangerous environments and they have also helped the handicapped lead more normal lives.

The contribution of teleoperators to the future may be more revolutionary. Consider how your life would be changed if you could project yourself to any spot on earth without getting in a car or catching a plane. The need for business travel would diminish drastically; travel would be mainly for pleasure, for a change of scenery. The essence of the teleoperator concept is the augmentation and expansion of human reach, human strength, and the human presence.

READING LIST

Bionics: The Science of Living Machines, Daniel S. Halacy, Holiday House, New York, 1965, 190 pp., $4.95. Grades 10–12.

Man's Place in the Dybosphere, Richard R. Landers, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1966, 266 pp., $6.95.

The Search for the Robots, Alfred J. Cote, Jr., Basic Books, Inc., New York, 1967, 256 pp., $5.95.

Science Journal, Special Issue: Machines Like Men (October 1968).

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