UNMANNED GROUND SUPPORT EQUIPMENT

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INTRODUCTION

The title which has been assigned to this paper is in a sense inappropriate, since the systems to be described are actually manned. The distinction between these "unmanned" systems and the "manned" systems described by the previous speaker lies in the location of the man. In the systems which will be discussed more fully in the next few minutes, the man who controls and directs all operations to be performed is located at a distance from the operation consistent with his personal safety and comfort. There is no technical upper limit to the distance which can separate the human operator from the job or function which he performs with the aid of a fully remote handling system.

It is recognized that one encounters a great variety of handling and manipulating requirements in connection with the supporting activities associated with nuclear-propelled systems. A corresponding variety of handling systems have been and are being developed. Good engineering clearly indicates a careful analysis of the particular situation leading to selection, on objective engineering grounds, of the general method appropriate under the circumstances. In this spirit, I would like to discuss more fully the "unmanned" fully remote-controlled type of system, not with the viewpoint that it is the ultimate answer to all remote handling problems, but rather that it is one of the methods available to the engineer. Since this type of system has been relatively little investigated, it seems worthwhile to explore its attributes and its potentialities more fully.

The first figure illustrates a typical, fully remote-handling system. The figure shows the Hughes Mark II Mobot Remote Handling System designed primarily for use in nuclear hot cells. This apparatus illustrates the complexity and versatility of which fully remote, electronically commanded systems are capable.

THE HAZARDOUS AREA PROBLEM

The problem of accomplishing ground support functions in the extremely intense radiation environment which accompanies nuclear propulsion systems is a special case of the more general hazardous area problem. This problem may be approached from a basic theoretical standpoint. For purposes of this brief discussion, I would like to outline a few fundamental points concerning the theory of hazardous area operations.

The second figure shows the simple basic geometry of any hazardous area. We see on one side of the illustration an area which is hazardous, meaning simply that it cannot be entered by personnel. The hazard may be nuclear radiation, extremely high or low temperature, extremes of pressure such as are encountered in the depths of the ocean, or extremes of vacuum such as are encountered in space. I am sure that you can readily visualize a number of additional hazardous areas in which it is preferable not to require personnel to enter.

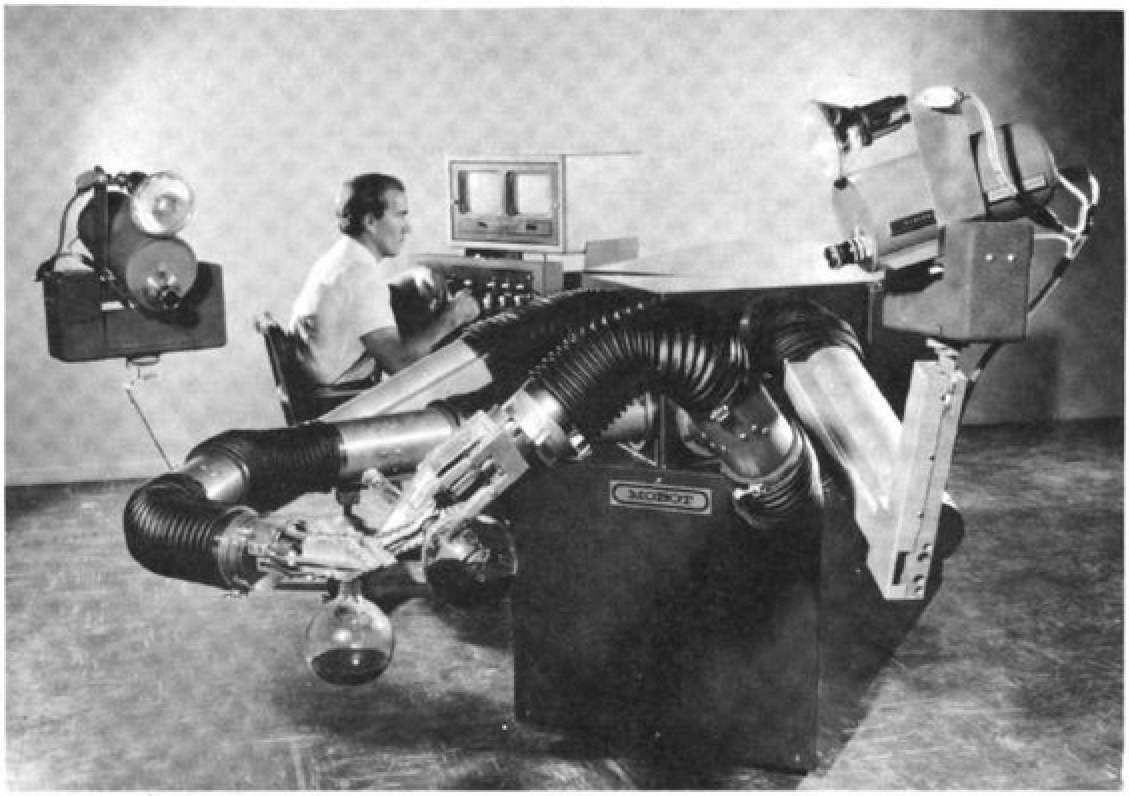

Figure 1. A Typical Electronically Commanded, Remote-Handling System

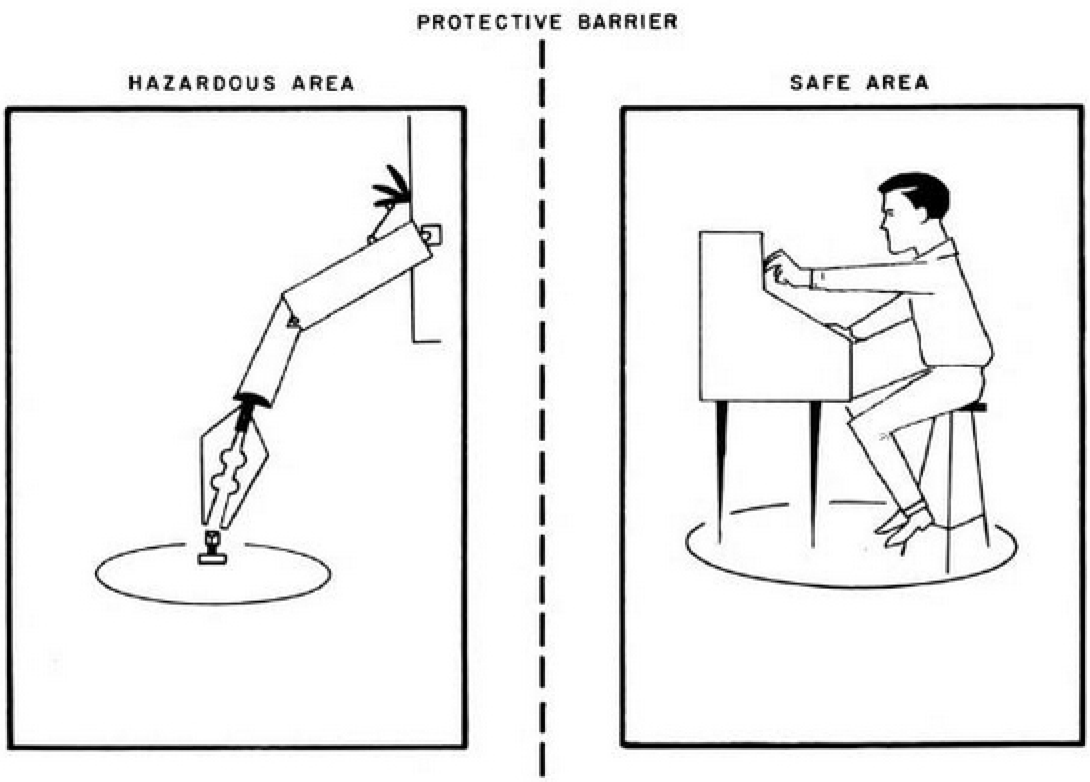

Figure 2. Generalized Remote-Handling Situation

Within the hazardous area is a function to be performed or a job to be done. This again can encompass the complete gamut of tasks normally performed by human personnel, either with their own hands or with the aid of tools.

Fundamentally, the hazardous area problem requires the design of equipment which will enable the human operator, who is shown in Figure 2 located safely and comfortably outside of the hazardous area, to perform any arbitrary operations within the hazardous area.

The almost infinite scope of possible operational requirements may be made manageable by the realization that all of these have in common the requirement to transfer and re-orient geometrical objects in space. In most cases this must be accomplished in the presence of fixed obstacles over which in general one has no control. Such terms as "manipulation" or "transfer operations" are descriptive of the tasks that human workers perform in assembly, maintenance, installation, and other functions associated with the over-all technology of ground support.

A different way to analyze this problem is to realize that a man, for purposes of the present discussion, consists of four separate functional systems. These are: his intelligence, his muscles, his senses, and his nerves. His muscles accomplish the manipulative functions mentioned above; his nervous system controls and directs the muscles and reports back via the sensory receptors the status of the objects being handled. Finally, of course, the intelligence gathers and analyzes the data transmitted to it by the sensory nervous system and transmits appropriate commands to the muscles via the nervous system.

The electronic technology available today can quite readily extend the length of the nervous system to any desired distance. The muscular system can be replaced by electronically controlled actuators (these may be hydraulic, electro-mechanical, pneumatic, or some combination of these). The sensory system can be extended by means of electronic transducers and data links.

In other words, the intelligence can be separated by any desired distance from the physical work which it is directing and performing by appropriate use of well-proven electronic technology. This is one way of stating the philosophy which guides one in the design of such systems.

So much for a basic outline of the theory and philosophy of fully remote-handling systems. Let us turn now to a more specific look at the engineering of such systems and at their capabilities.

CLASSIFICATION OF REMOTE-HANDLING SYSTEMS

As noted above, there are a number of ways which have been developed and which are under study for accomplishing functions in hazardous areas. One method of classification of these systems will be discussed in this section. There are of course a very large number of bases for classification of remote-handling systems. This writer, however, has found that the one presented here is quite useful as a guide for selecting systems in a given situation.

The three classifications are as follows:

1. Direct-vision systems
2. Programmed systems
3. Fully remote systems

Each of these will be briefly discussed in the following sections.

Direct-Vision Systems. This category includes all situations in which it is feasible for the operator to see directly into the hazardous area. The familiar nuclear hot cell is of this type, as is the glove box familiar both to chemical and nuclear technology. Upon a little reflection, one can readily discover a large number of other hazardous area handling methods of this type.

The tools used in direct-vision systems are, in effect, extensions of the human arm. A few examples are the master-slave manipulators of nuclear hot cells, the great variety of cranes and hoists employed in steel mills, foundries, shipyards, and the like, the protective gloves used in connection with glove boxes, and the forceps and tongs which may be employed when the hazard is a relatively mild one. For purposes of this analysis, the electrically powered, general-purpose manipulators which are often found in the larger nuclear hot cells are to be considered as electrical tongs, and serve the same system function as does a mechanical tong.

Direct-vision systems are often relatively inexpensive and should be employed whenever the situation permits. However, when one deals with an extremely severe hazard, the cost associated with suitable protective windows and the handling disadvantages associated with the mechanical or electrical tongs may indicate that one of the other systems is to be preferred.

Programmed Systems. In complete contrast to the direct-vision systems discussed in the preceding section, one sometimes finds fully automatic programmed systems to accomplish a pre-determined sequence of operations in a hazardous area. In this case, the man cannot see into the area nor reach into it; it depends entirely on pre-determined decisions built into the machine itself. One example of such a machine is the reactor refueling devices which can accomplish very complex sequences of mechanical motions in withdrawing a spent reactor fuel rod and replacing it with a fresh one. Such machines in operation will often appear to have a limited degree of intelligence, since their motions are very complex and they may even make very minor pre-determined decisions. In general, they are quite expensive and completely incapable of dealing with any unexpected development. The choice between a programmed system and one of the other types should ideally be made on the basis of careful comparative economical analysis.

Fully Remote-Handling Systems. One often hears discussions, which sometimes become acrimonious arguments, concerning "man vs. machine." These arguments usually revolve around a choice of a man or a machine to accomplish a given function in a hazardous environment. In the terms of our current definitions, this is actually a discussion of the relative merits of direct-vision systems and programmed systems.

Fortunately, a third alternate is possible which makes fullest use of the unique intelligence and decision-making ability of the human mind without requiring the man himself to be exposed to any hazardous environment, and without requiring the use of massive amounts of shielding or protective materials. These are the systems, of which an example was shown in figure 1, which may be described as fully remote, electronically commanded handling systems. We have coined the term "Mobot systems" as a somewhat less mouth-filling title for this third type of remote-handling system.

As mentioned above, the principal purpose of this paper is to present the basic design methods and the present and potential capabilities of Mobot handling systems in context with the alternate methods available for accomplishment of ground support functions within the nuclear environment. The section which follows will present an analysis of the major functional parts of a Mobot handling system.

ENGINEERING ANALYSIS OF FULLY REMOTE (MOBOT)-HANDLING SYSTEMS

For purposes of analysis and engineering design, it is desirable to divide any fully remote-handling system into six fundamental functional subsystems. These are:

1. The manipulation subsystem
2. The sensory subsystem
3. The locomotion subsystem
4. The command and data link
5. The control console
6. The power subsystems

Each of these will be discussed briefly below. Figure 3 shows the interrelation among these subsystems for the cable-controlled case; Fig. 4, for the radio-controlled case.

When after careful economic and engineering analysis a Mobot system appears preferred in a given situation, the detailed engineering of the system is best carried out by separately attacking the six subsystems just named, and of course integrating these into one effective, reliable, and economic handling system. The following sections will very briefly point out the principal requirements upon the six subsystems and present and future capabilities of each.

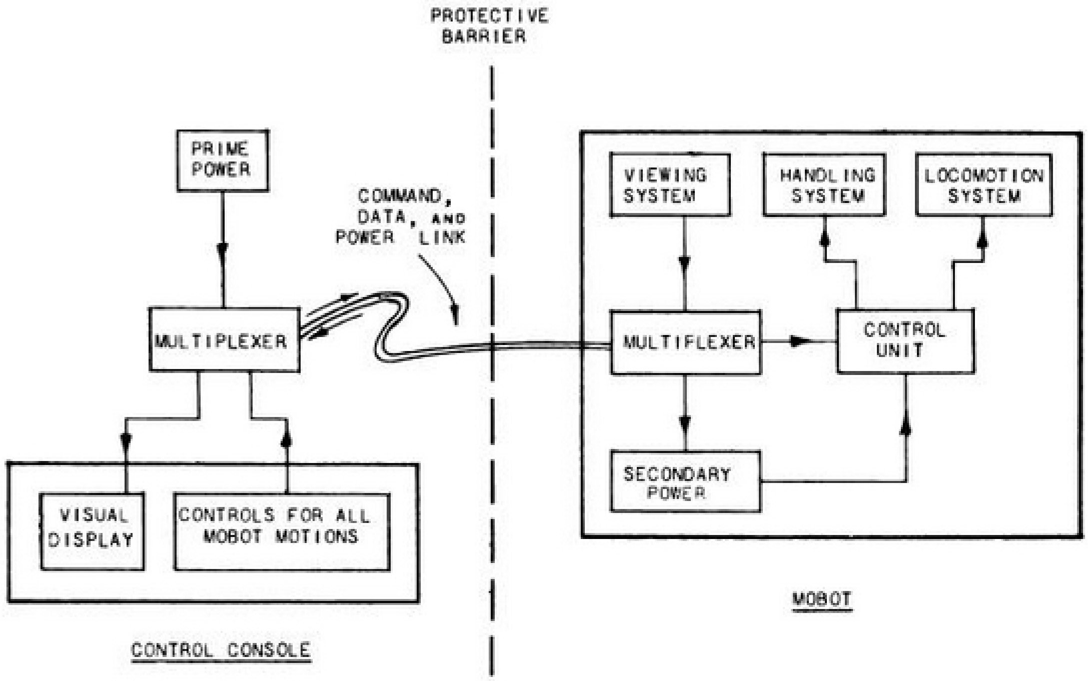

Figure 3. Generalized Block Diagram of Remote-Handling System (Cable-Control Type)

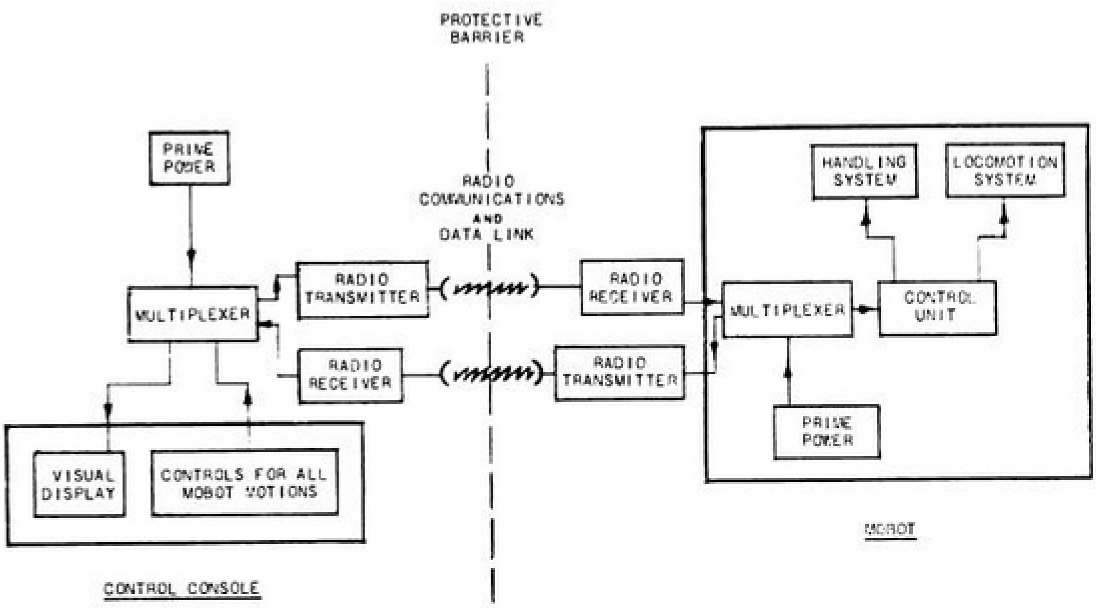

Figure 4. Generalized Block Diagram of Remote-Handling System (Radio-Control Type)

The Manipulation Subsystem. One could hardly avoid the use of anthropomorphic terms like "hands" and "arms" to describe those portions of a Mobot system which accomplish the actual manipulations. These devices in general do not resemble the human arm in detail, and indeed as progress is made in this portion of the remote-handling art the handlers depart more and more from the geometry of the human arm and hand. The requirements, of course, are difficult to state in detail, but easy to state in general. The manipulating system should be able to grasp an object of arbitrary size, shape, and weight, and to displace and rotate it an arbitrary distance in the presence of arbitrary obstacles. The engineering problem is to design structures of the necessary geometrical versatility which are also mechanically rugged and reliable. One example of an attempt to accomplish great versatility in the geometrical sense is the Hughes Mark II arm shown in Fig. 5. Numerous other arm geometries and structures have been developed; there is enormous room for ingenuity and progress in this area.

A truism which seems to be of quite general applicability in manipulation consists of the undesirability of combining extremely complex manipulation with ability to lift very heavy weights. These two requirements are to a very large extent incompatible. Hence, it is usually desirable to furnish separate handling mechanisms for complex and delicate motions from those to simply lift and translate heavy objects. The cross-over point between the two is arbitrary; somewhere between 25 and 100 pounds appears logical, mainly because this is about the place at which the human arm (as a versatile general-purpose manipulator) is replaced by hoists, derricks, or jacks as simple heavy lifters.

A properly engineered handling system can employ the tools of the rigging trade in very much the same way as is done today by human riggers. These tools may in some cases be operated by the electronically controlled hands. In other cases, they are directly integrated into the command system. I will show later an example of a handling system making use of this principle of separation between manipulation and lifting.

The Sensory Subsystem. This subsystem includes all the information-gathering devices located in and around the hazardous area which collectively inform the human operator of the situation of his Mobot vehicle and enable him to direct and control it. Probably the most important of the senses is vision; this, however, is supplemented by judicious use of other human and non-human senses, such as hearing, touch, temperature, nuclear radiation level, ambient pressure, and a great variety of other measurable physical variables.

For this brief discussion, I would like to concentrate upon vision. The principal requirement of the visual portion of the sensory subsystem of a Mobot remote-handling system is to inform the operator of the relative positions in space of the Mobot vehicle itself and of the objects with which it is working. One method of accomplishing this is to employ two or more conventional closed-circuit television camera systems.

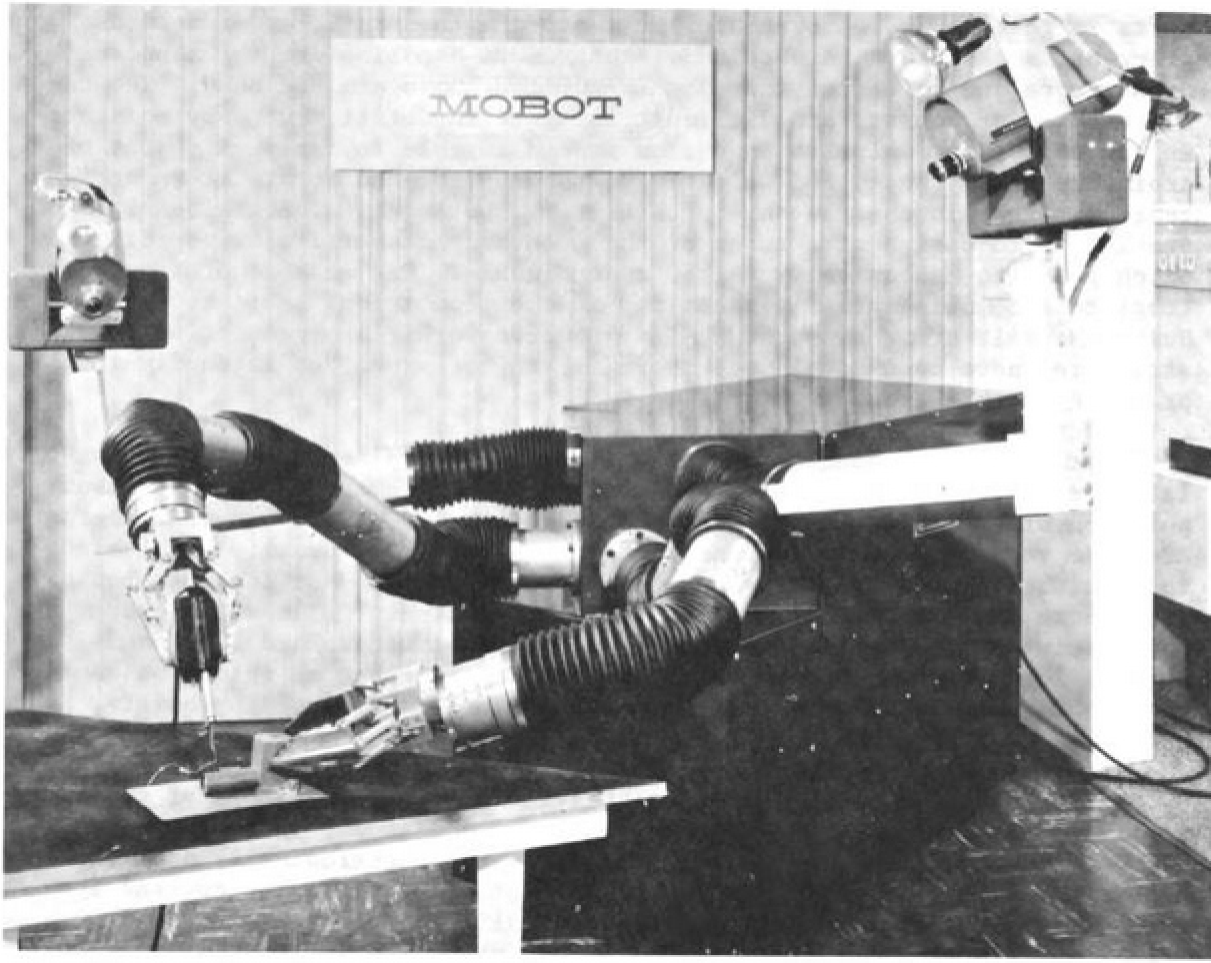

Figure 5. A Mobot Remote-Handling Vehicle Using a Soldering Gun

Comparison of the information presented to the operator upon the several monitor screens corresponding to the several cameras will enable him to determine, unambiguously, the location in three dimensions of all objects with which he is concerned. To do this requires proper location of the cameras and ability to move and point the cameras to react to differing situations.

To clarify this point somewhat, let us consider one typical and basic situation as illustrated in Fig. 6. The problem is to grasp with the machine's tong an object which is to be transferred to another location. This requires the operator to be aware of the three spatial coordinates separating the tong from the object. Two TV cameras, so located as to observe the working area from mutually orthogonal directions, permit the operator to make this geometrical calculation.

It is an interesting and perhaps surprising fact that this calculation in solid analytic geometry can be readily learned, and that after a few hours of practice the operator becomes completely unaware of the rather artificial relationship between his two TV pictures and the working scene. A skilled operator obtains from his TV monitors a subjective impression of the three-dimensional orientation of objects in view exactly as vivid and as easy to work with as the subjective impression which we obtain from our own two eyes. This is a dramatic illustration of the extreme flexibility of the human mind.

The use of operator-positioned TV cameras for driving and steering is equally subtle; sufficient experience has now been gained to prove beyond a shadow of a doubt that both driving and steering operations and handling and manipulating operations can be accomplished accurately and reliably by a trained operator employing TV systems of the type briefly described herein.

Locomotion. The function of moving the entire Mobot vehicle about can and should be clearly separated from the manipulating function. The locomotion systems to be employed are those which have been developed for many other uses. When circumstances permit, a conventional vehicle chassis adapted for remote control will be employed. This may be either an indoor vehicle, such as the Mobot Mark II vehicle shown earlier, or any of the familiar on-road or off-road vehicles which are, of course, in very wide use already.

Sometimes it is not feasible to use a wheeled vehicle. In such cases, a three-axis mount, similar to that of a bridge crane, may be employed. When space is limited, a wall- or ceiling-mounted boom may be preferable to a three-axis mounting.

In the undersea environment, one employs floating vessels driven by screw propellers for mobility; this is usually preferable to vehicles which roll or crawl on the ocean bottom. In the space situation, one may employ small rocket motors or compressed-gas jets to obtain mobility in the gravity-free environment.

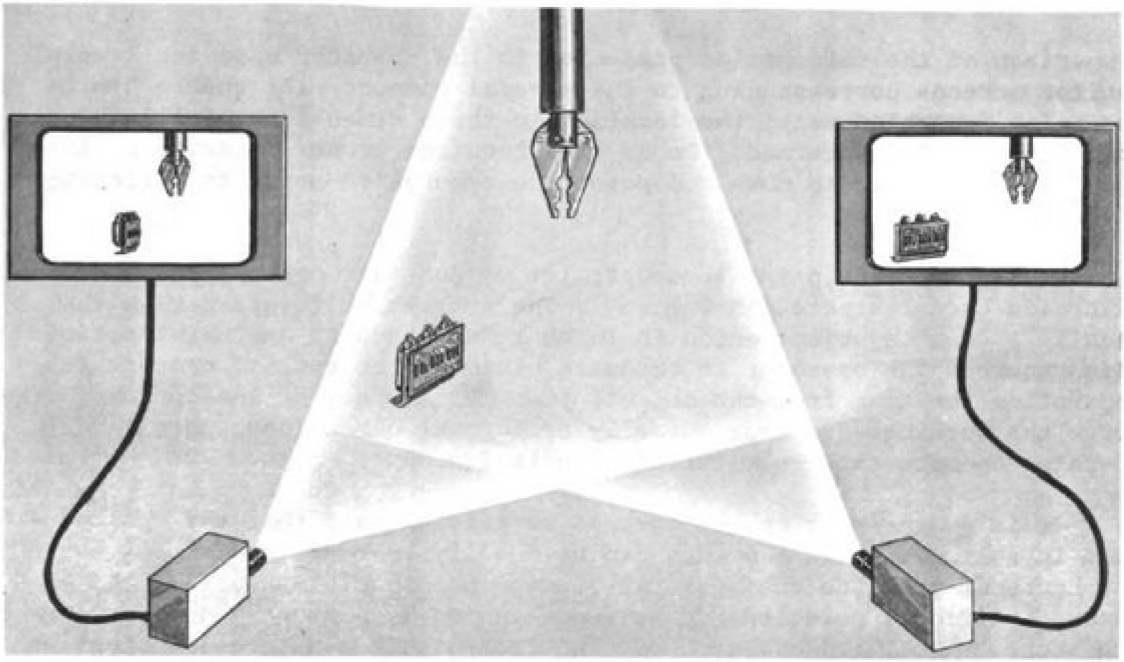

Figure 6. The Two-Camera System for Obtaining Spatial Information

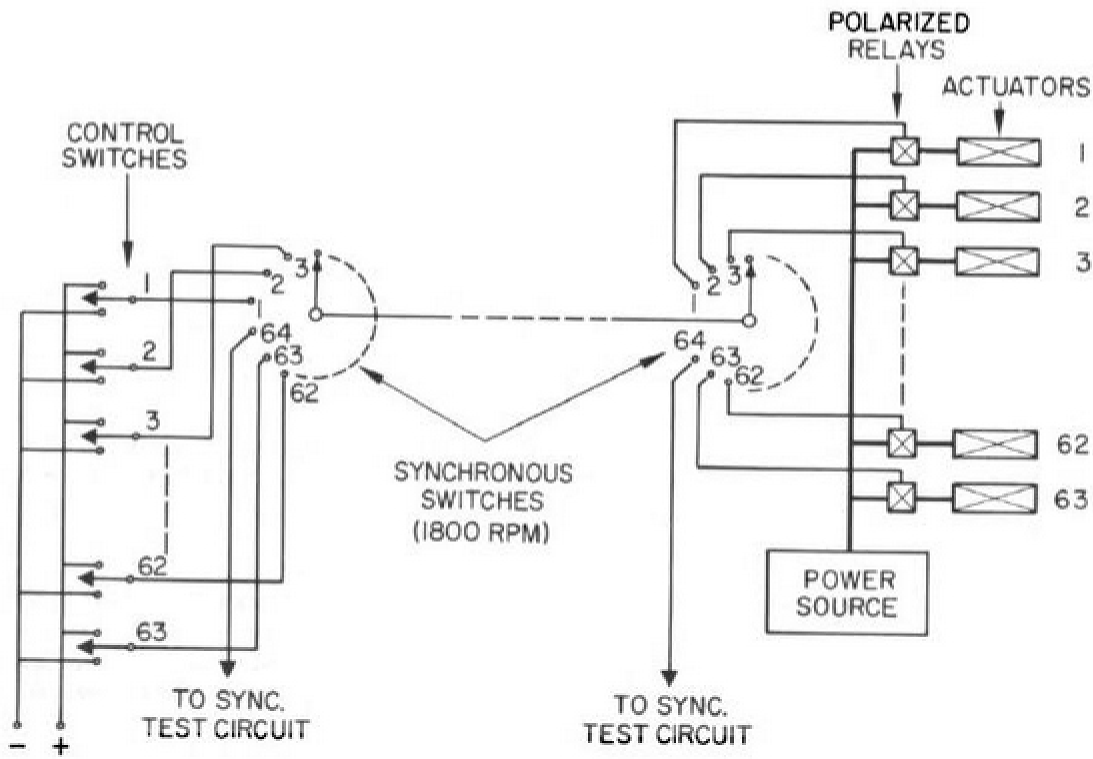

Figure 7. Trinary Coding Command System

Thus, the design and selection of the locomotion subsystem is accomplished after over-all analysis of the environment by selection from well-proven locomotion methods.

The Command and Data Link. This subsystem is the counterpart of the human nervous system, and is essential for two-way communication to transmit commands from operator to Mobot vehicle and to transmit sensory data as discussed above from vehicle to operator. The data link employs conventional and well-proven techniques adapted from communication and telemetry.

A command system which has worked out quite well in practice is the trinary-coded digital command system shown in Fig. 7. This system employs trinary pulses to control the motions of all the moving parts of the Mobot vehicle. A trinary pulse is one which has three possible states, namely, +1, 0, or -1. For Mobot command system purposes, this is preferred to the more familiar binary system, since most elements of the remote system have three normal states rather than two. The normal states are, of course, stationary, moving forward, or moving backward. Almost any moving part has two directions of motion which of course cannot be actuated simultaneously. Therefore, the trinary system is logical and economical.

The fundamental features of this type of command system are shown in Fig. 8. In effect, the system accomplishes a one-to-one correspondence between switches on the operator's control console and motions on the remote vehicle. In the multiplexing system, these signals are converted to trinary code and are then commutated and transmitted on a time-sharing basis. At the vehicle, these are de-commutated and directed to the appropriate actuators.

The command information transmitted to the Mobot vehicle is a train of trinary pulses which, 30 times a second, command a new configuration of rest or motion; see Fig. 9. Experience has shown this command rate to be completely adequate to give the operator full control of very complex motions and manipulations.

This trinary coding system offers all the advantages of any digital system in that it is relatively invulnerable to fading and distortion in the command link. It is also quite economical of bandwidth. The distance over which the trinary-coded commands can be transmitted is essentially unlimited. Conventional radio or telemetry systems can be used for transmitting these command signals. The exact frequency and power to be employed is determined by the distance, the terrain, and the availability of frequencies for the function in question. This is in no wise different from the selection of a two-way radio communication link for any more familiar purpose.

The Control Console. The control console is the man-machine link. It incorporates the display devices by which the Mobot vehicle informs the operator of its location and circumstances and the operating handles

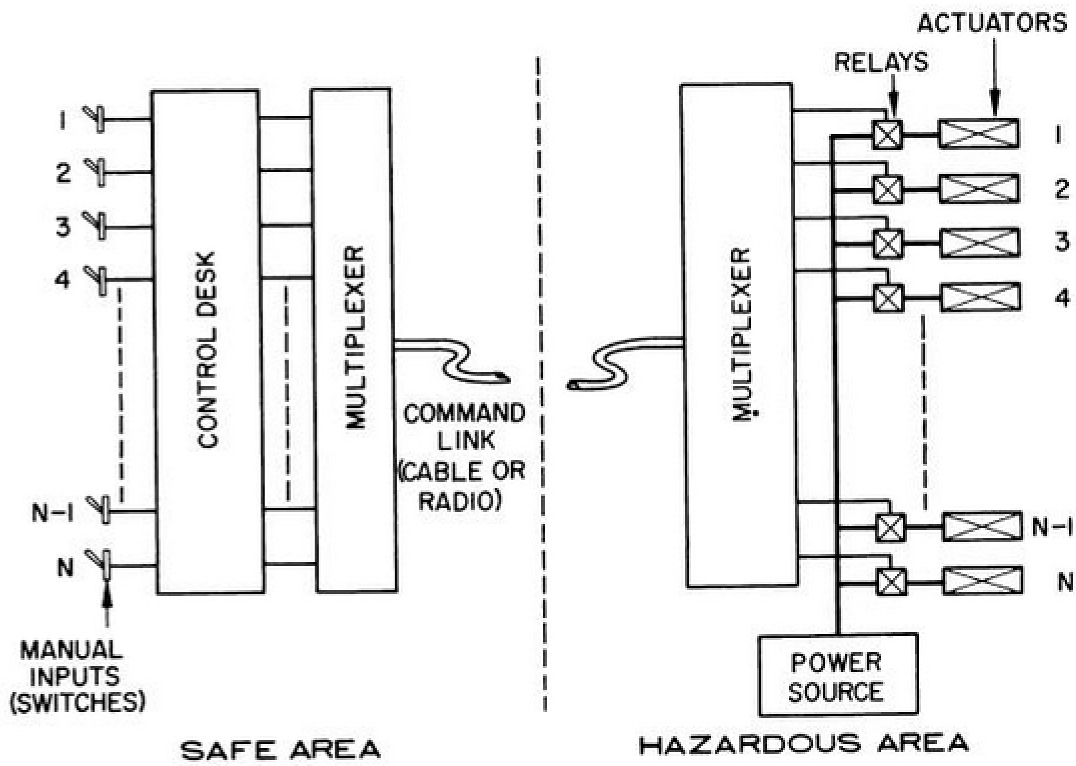

Figure 8. Command System Analysis

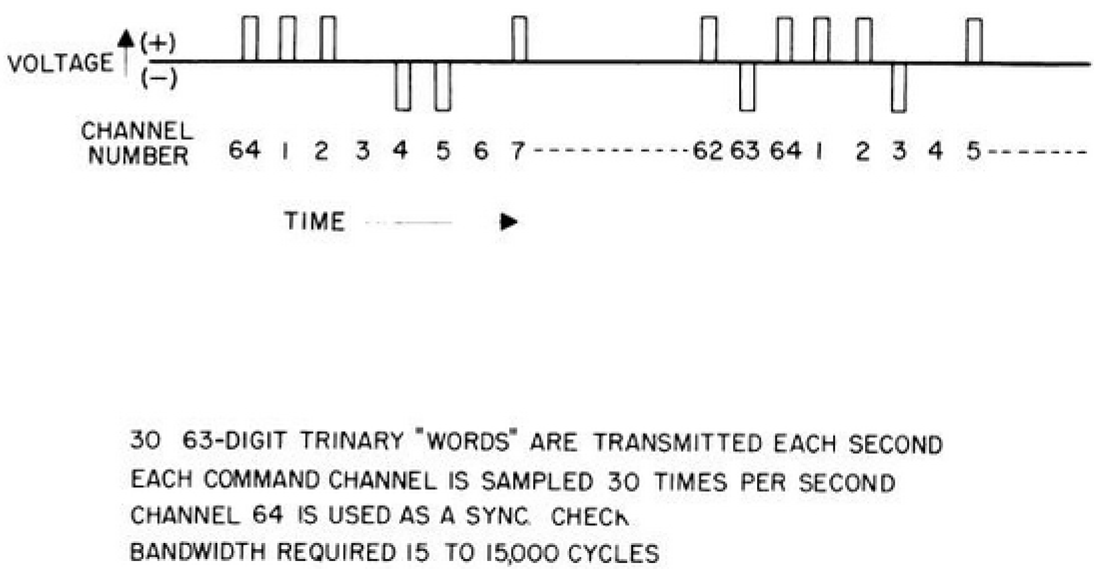

Figure 9. Trinary Coded Commands

for the command switches by which the operator communicates with the machine. One example of such a console is shown in Fig. 10. This is the control console for the Mark II Mobot system and illustrates the use of four-position toggle switches for commanding a great variety of motions. This console has proved quite satisfactory in operation. We have also worked with pistol-grip type controls in which a large number of functions are centralized on a single pistol grip capable of a corresponding variety of motions. A great deal of additional research is required to determine a truly optimal control console configuration with due regard to ease of learning, ease and comfort of operation for long periods, and other factors involving an inter-relation of psychology, human factors engineering, and electronic engineering.

Power Subsystems. The power which causes the remote vehicle to move about and to displace objects, as well as the power to operate the sensory and display systems, is perhaps well considered last in the sequence of design. One always finds more than one power subsystem, since the vehicle itself must carry at least auxiliary power on board. In systems which employ a cable for communication between operator and vehicle, this same cable may well be used to transmit electrical prime power. This is almost always a desirable system when circumstances permit its use. Radio control systems, of course, must carry a prime power source on the mobile vehicle. This may be an internal-combustion-engine-driven generator or, in extreme cases, a nuclear power plant. A Mobot engineer will select from proven power technology that combination of prime and secondary power systems which will accomplish his functions most economically in terms of cost, gross weight, and bulk.

EXPERIENCE WITH FULLY REMOTE HANDLING SYSTEMS

A brief summary of experience to date with fully remote-handling systems may clarify and make meaningful the rather theoretical discussion of the preceding sections.

The Hughes Mobot Mark I, which was delivered to Sandia Corporation in the latter part of 1959, has now been in use at that laboratory for over a year. This machine is shown in Fig. 11. It is a heavy machine, capable of lifting and handling 150 pounds, and of lifting (but not handling) 1500 pounds. It is a cable-controlled machine for use in a large hot cell and, when used in association with master-slave manipulators, offers very great versatility. It is noteworthy that the net cost of the hot cell making full use of the Mobot concept is very substantially less than that of a comparable hot cell employing direct-vision type manipulation alone.

Another example shown in Fig. 12 in a completely different field of application is the RUM or Remote Underwater Manipulator built by Scripps Institute of Oceanography for the Office of Naval Research. This heavy vehicle, equipped with a single crude arm, has demonstrated the feasibility of fully remote operation on the ocean bottom.

Figure 10. Mark II Control Console

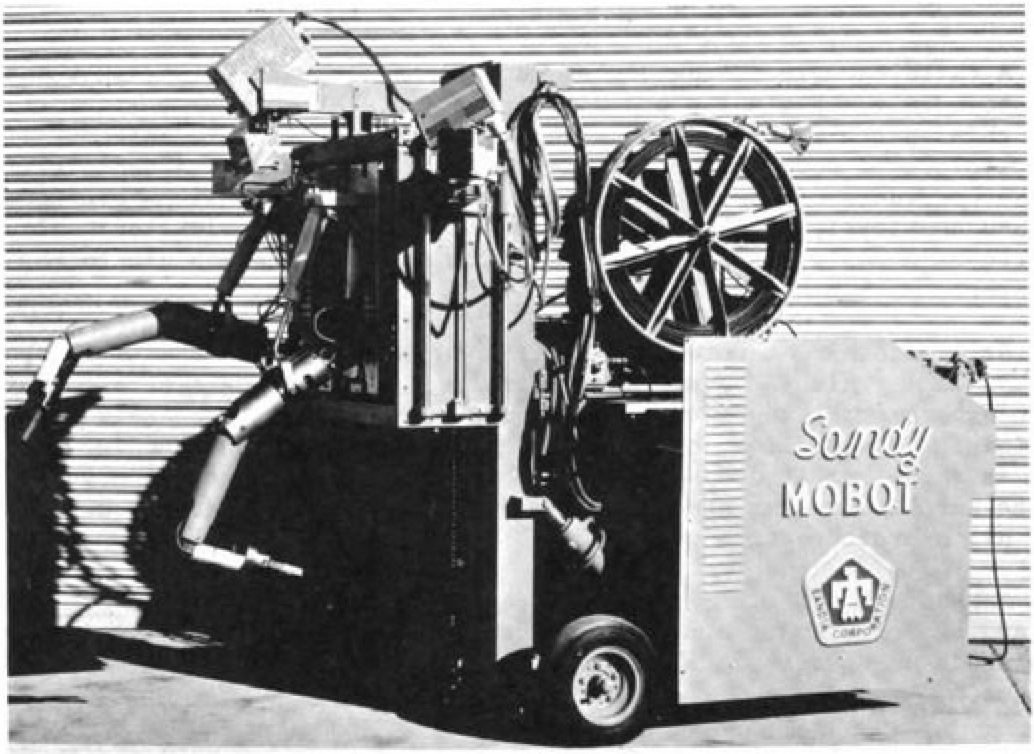

Figure 11. The Mobot Mark I Heavy-Duty, Remote-Handling System

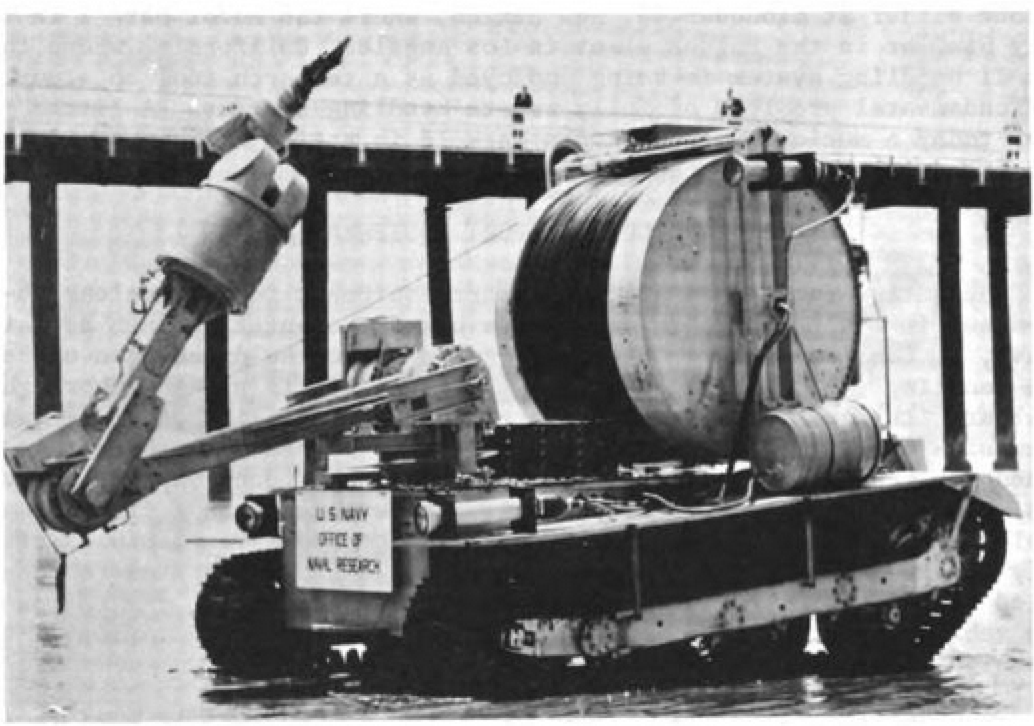

Figure 12. The RUM, a Remotely Controlled, Underwater Handling Vehicle

A third example is the Hughes Mark II Mobot handling system which was shown in the beginning of this discussion. Figures 13, 14, and 15 show this system accomplishing several typical handling functions. It has also proved completely feasible to drive and steer this vehicle within the corridors of our laboratories. All of these functions are accomplished completely by electronic command and data communication employing a three-wire cable as the only link joining the remote vehicle to the operator.

Still another example of a partial-remote-commanded system is shown in Fig. 16. This is a remotely controlled earth-moving system operated in an experimental way by the Army Corps of Engineers, Fort Belvoir, Virginia. This machine, of course, does not include the handling function as such, but it does exhibit all the other attributes of a fully remote-handling system and, in spite of its rather primitive viewing methods, has operated satisfactorily.

A remotely controlled street-sweeper employing television for guiding and steering and a simple frequency coded command system has recently completed successful tests at Air Force Special Weapons Center in Albuquerque.

These experiences give rise to the confidence expressed earlier in the complete feasibility and operability of fully remote-handling systems when applied to situations where the over-all analysis indicates such systems to be preferred. The most effective verification of these statements comes from seeing a fully remote-handling system in operation; this can be done either at Albuquerque, New Mexico, where the Mobot Mark I is in daily use, or in the Hughes plant in Los Angeles, California, where the Mark II handling system is being employed as a research tool to study the fundamental problems of fully remote-handling systems. A little later today a motion picture of the Mark II in action will be shown as concrete evidence of its capability.

A TYPICAL GROUND SUPPORT EQUIPMENT DESIGN

The entire subject of ground support equipment in the nuclear environment is far too vast to cover in a brief presentation such as this. I have, in fact, chosen to use most of my time in the discussion of remote-handling systems as such, since this audience is already thoroughly familiar with conventional and nuclear GSE. I would like to close this discussion by showing a typical design concept of a Mobot vehicle designed for general-purpose application to nuclear ground support activities. This is shown in Fig. 17. It is presented not as a firm and final design, but as a typical design to illustrate the principles of fully remote-handling systems and to serve as a starting point for detailed analysis of specific GSE problems. An orthographic projection of this vehicle is attached hereto, for a more detailed presentation of its dimensions and capabilities.

The vehicle shown has selected an off-road chassis to permit it to

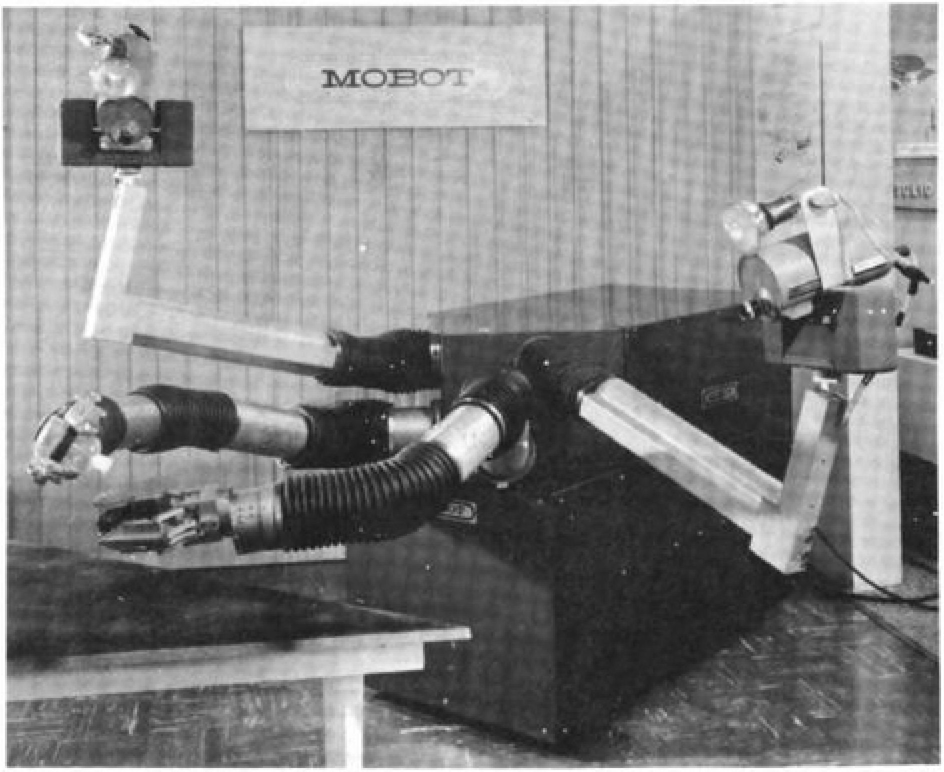

Figure 13. The Mobot Mark II Executes a Pouring Operation.

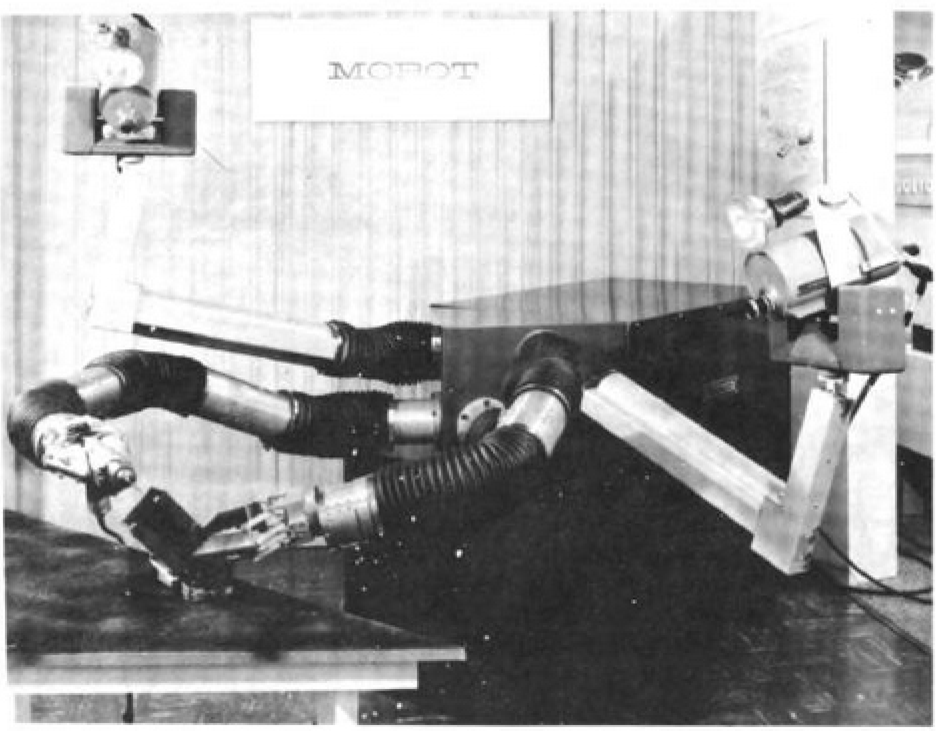

Figure 14. The Mobot Mark II Operates an Electric Handdrill.

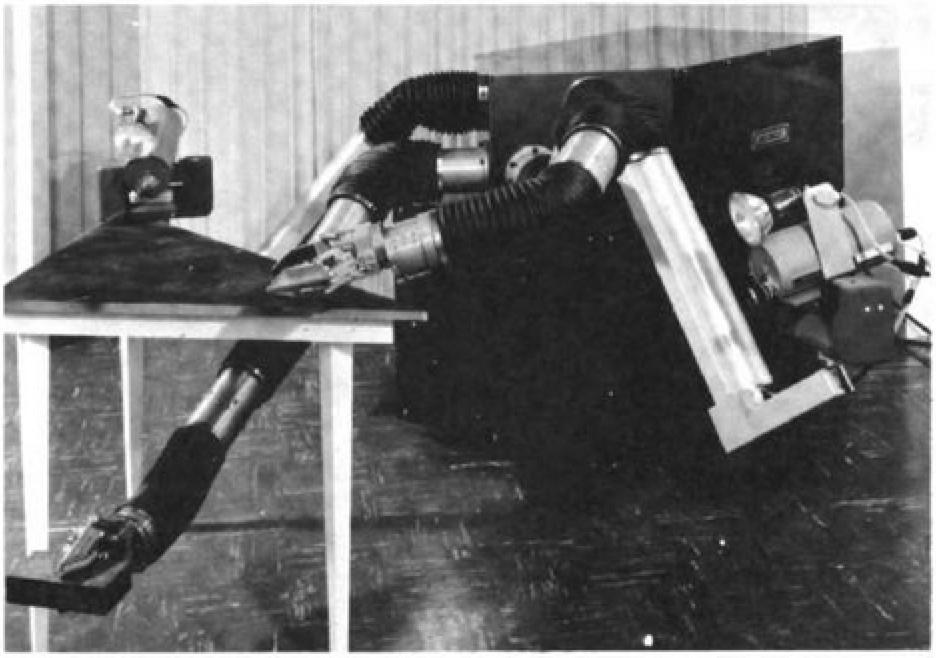

Figure 15. Mobot Mark II with 25-Pound Lead Brick at 5-Foot Arm's Length

Figure 16. A Remotely Controlled Bulldozer

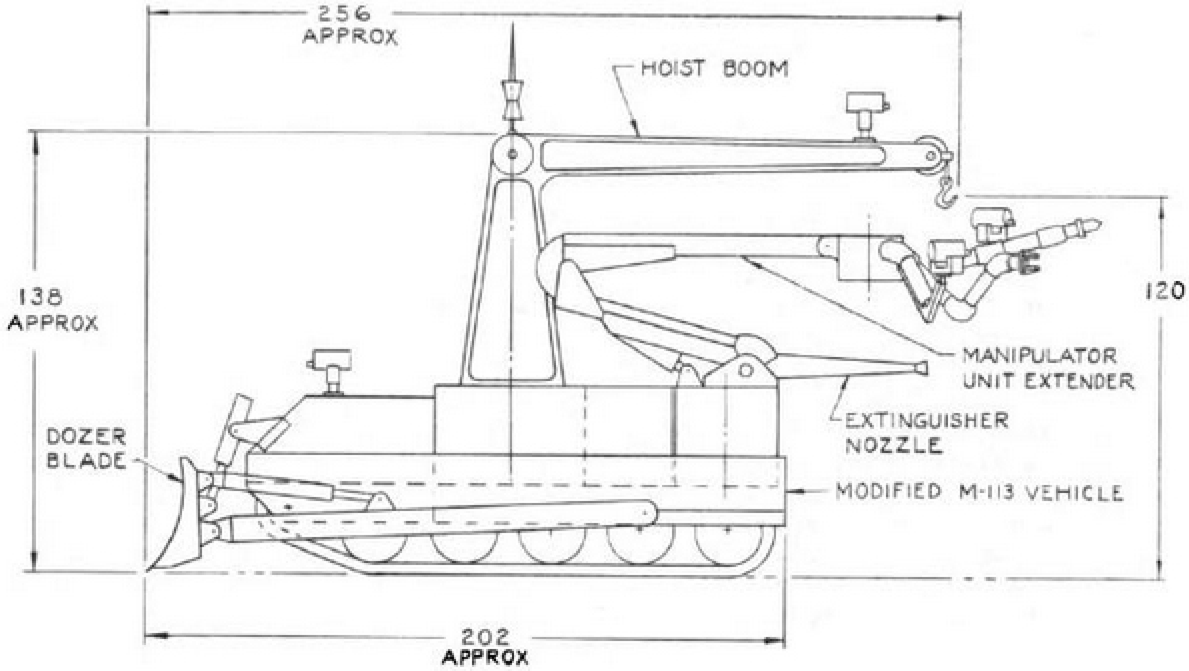

Figure 17. A General-Purpose, Radio-Controlled, Manipulating and Rescue Vehicle

operate in areas where a good paved surface may not be available. A gasoline or Diesel-powered prime mover furnishes both traction power and auxiliary power at the vehicle. A radio command and data link is employed. There is no limit to the separation between operator and vehicle.

It is highly desirable in most cases where a small number of fixed operating sites are involved to provide each site with hard-wire communication with the operating point. Wire communication is usually preferable to radio because of the complete elimination of any interference problems, and because of the fact that one can transmit electric power at the same time. In a system such as the one shown, one would drive the vehicle to the operating site by radio command and at the site would employ the vehicle's remotely controlled manipulator to insert a plug into the socket provided. At this point, the command system is switched over from radio to cable control and the power system is switched over from internal-combustion to hard-wire. These switch-overs are very readily accomplished with the trinary-coded command system.

Manipulation is accomplished by Hughes Mark II arms identical with those shown in the earlier figures. These very versatile arms are mounted upon a jackknife boom enabling them to reach operating sites as high as 25 or 30 feet from ground level. The arm assembly can also be moved about within a 25-foot radius circle without the necessity of moving the prime vehicle.

The two TV cameras which enable the operator to accomplish detailed manipulations are mounted upon the same turret assembly as the handling arms. Thus, the entire assembly of "arms" and "eyes" moves about together and may be positioned and oriented most favorably for any given job.

Additional TV's and other sensors, such as the gamma-ray telescopes, are mounted upon the basic vehicle and are employed primarily for driving and steering it to the operating site. The vehicle can, of course, be equipped with any additional sensors that may be desired.

A jib crane for lifting and handling heavy objects is mounted upon the vehicle. The manipulating arms may be used to engage or disengage the crane hook as required. Objects weighing up to a few hundred pounds can be handled in this way; objects weighing more than this should, in general, be handled by separately designed, remotely controlled, heavy-lifting mobile mechanisms.

The trinary-coded command system discussed above is perfectly capable of handling this very complex system. One would probably find, however, that two or three operators working as a team would be needed in order simultaneously to handle its many degrees of freedom.

CONCLUSION

In this brief discussion it has been possible only to outline the main points applicable to fully remote-handling systems. If this presentation leads to fruitful discussions and to exploration in more detail of the many interesting questions associated with fully remote-handling systems, it will have accomplished its intended purpose.