TECHNICAL MEMORANDUM 627

THE MOBOT: A FULLY REMOTE, MOBILE HANDLING DEVICE

27 November 1959

Nuclear Electronics Laboratory

HUGHES

HUGHES AIRCRAFT COMPANY
CULVER CITY, CALIFORNIA

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ACKNOWLEDGEMENT

The successful operation of Mobot Mark I was due to the engineering skill and hard work of a number of people. Particular recognition should be made of the contributions of Mr. Vaughn E. Thompson to the mechanical design and physical construction of the Mobot, to Mr. Don A. Campbell for the design and construction of the electronic circuitry, and to Mr. Stanford E. Pearlman for his skill in operating the Mobot and his contributions to its construction.

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ABSTRACT

The need for a fully-remote mechanism to perform hazardous operations has long been recognized. Recent experiments have demonstrated the complete practicability of mechanisms in which the operator's only contact with the remote mechanism is by electronic means. The term "Mobot" (Mobile Robot) has been coined as a generic name for such devices. Mobots give the operator vision by a novel employment of conventional closed-circuit television systems, and control by an electronic command system.

Mobot Mark I is the first device to employ the Mobot concept. It is described in some detail. The successful operation of Mark I has led to engineering studies of more advanced vehicles for the nuclear, underwater, and space environments.

1. THE MOBOT CONCEPT

The Mobot concept stated in general terms is as follows: To perform physical work in a hazardous area it is not necessary for a man to enter; his senses and his ability to manipulate can be introduced into the area by electronic means. This enables his intelligence and judgment to be applied without exposing him to any physical hazards.

A man can be considered, for purposes of analysis in connection with control systems and the like, to be composed of three elements: A number of actuators, a sensor system, and a computer. The actuators and sensors can be duplicated or even improved upon by electronic means. It is the computer, with its judgment and memory, which cannot even be approached in capability by any electronic device known today. In connection with hazardous areas, this indicates that it is feasible to extend the actuators and sensors (the "arms" and "eyes") of a man into the hazardous area, while leaving the computer (and also the man himself!) safely outside. This is another way of stating the Mobot concept.

The Mobot falls half-way between mechanical devices like the ANL master-slave manipulators, and the robot of science fiction which has a "brain" making it practically self-sufficient. The Mobot concept is a completely new approach to problems of remote handling and hazardous operations; its implications are only beginning to be appreciated.

The science and technology and inventions which, collectively, make Mobots possible constitute a new branch of engineering which may be referred to by the term "Mobotry". Almost limitless scope for research and invention is to be found in this new and almost unexplored technical area.

2. GENERAL DESCRIPTION OF MOBOT MARK I

The Mobot Mark I, which was developed to meet a particular requirement in a nuclear radiation laboratory, is an application of the Mobot concept. This TM is primarily concerned with a description of the Mark I Mobot and the way in which it has been used. This is presented both as a mechanism which is interesting in itself, and as the first concrete application of the Mobot concept.

Figure 1 is a photograph of Mobot Mark I. This figure shows the Mobot itself with its handling arms, its TV cameras for vision, and its cable reel, together with the control console from which the operator controls all motions of the vehicle. The 200-foot cable through which the operator controls the Mobot can also be seen.

Mobot Mark I was developed for use in the SERF (Sandia Engineering Reactor Facility). This facility includes a large hot cell, approximate dimensions 50 x 100 feet. One wall of this hot cell is lined with radiation-resistant windows through which its interior can be observed. Each window is equipped with a pair of ANL Mod. 8 manipulators. A heavy concrete door separates the hot cell area from the radiation area. The principal tasks assigned to the Mark I Mobot involve moving apparatus from one part of the hot cell to another. For example, it can enter the radiation area and remove an irradiated item from this area to the hot cell. The Mobot will then remove any protective covers, such as shielding coffins, and transfer the test specimen to one of the working areas where delicate dissections and analyses can be performed manually by the Mod. 8 manipulators. The Mobot will also be used for setting up or removing special items of test equipment at the operator positions. Thus it is intended to supplement the Mod. 8's and to make these more effective.

An additional requirement upon the Mark I is that it must be able to lift a gross weight of 1500 pounds. The considerable size and weight of Mark I were necessitated by this latter requirement.

Table I gives the principal specifications of Mark I.

3. THE PRINCIPAL SUBSYSTEMS

Any Mobot has the following seven quite separate subsystems:

1. Perception
   (vision, hearing, touch, and proprioception)

2. Locomotion

3. Handling

4. Command System
   (multiplexing system and command and data links)

5. Power Systems

6. Cable Handling System
   (not needed in radio-controlled Mobots)

7. The Operator's Console

An analysis of any remote handling problem is facilitated by consideration of the above seven subsystems separately. It is usually possible to assemble proven Mobot components to accomplish a great variety of remote functions.

The sections which follow describe the seven basic subsystems of Mobot Mark I.

3.1 Perception

3.1.1 Vision. Most important to accomplishing complex remote operations is a vision system which will give adequate perception of relative spatial orientation. The Mobot vision system is based upon the discovery that completely adequate information can be obtained by the use of two standard closed-circuit TV cameras. Figure 2 shows the geometrical principles involved in this system. The two cameras view the working area from mutually perpendicular directions. Each camera displays upon a separate monitor the projection of the working area which is presented to it. Comparing these two projections, together with a knowledge of the location of each camera, enables the operator to determine the relative position in rectangular orthogonal coordinates of any objects within the field of view.

The situation illustrated in Figure 2, in which a handling tong is about to grasp a small electronic assembly, is completely typical. The operator must know the three relative spatial coordinates defining the vector distance between the two items. This information allows him to operate the controls in such manner as to bring the handling claw into coincidence with the object to be grasped.

It is clear that all the geometrical information required to perform this computation is available to the operator as he compares his two monitor screens which are mounted side by side. As operators gain facility with practice, this computation becomes more and more effortless until it becomes completely automatic and the operator subjectively "sees" any objects in the field of view in their correct relative spatial orientation. In other words, this new way of seeing is one which can be learned in a few hours of practice and which is completely compatible with human learning processes.

To facilitate the use of this system, the two TV cameras are independently mounted. Each can be rotated about mutually perpendicular axes so as to choose any desired field of vision. In the language common among TV engineers, the operator is provided with independent remotely-controlled "pan" and "tilt" for each camera.

When driving the vehicle, detailed perception of spatial position is much less important. For this purpose the cameras are usually pointed straight forward or straight aft, and the operator drives and steers the vehicle in much the same way as he would perform these operations were he physically seated upon it.

3.1.2 Hearing. Mobot Mark I is equipped with a standard two-way intercom system utilizing an RF carrier. This is multiplexed upon the cable, as described in Section 3.4. This system enables the operator to hear the operation of the Mobot's relays and controls, as well as any sounds in the hot cell. If it were ever necessary (as for instance, during maintenance) to communicate with someone near the Mobot, it can be given a "voice" by simply actuating the "talk" switch on the control console.

3.1.3 Touch and Proprioception. Mobot Mark I provides for neither of these. Quite satisfactory operation is attained by substituting vision for both of these senses. Either or both can be furnished if required.

3.2 Locomotion

The mobility of a Mobot is one of its basic features. In Mark I this was obtained by adapting a standard forklift chassis to remote control. This chassis utilizes a rear-drive-and-steer system particularly suitable for maneuvering in close quarters. The drive and steer controls on the operator's console duplicate those originally provided on the vehicle itself. The operator has four speeds forward or reverse and can steer $\pm 90^\circ$ from straight ahead.

This vehicle has full power steering, which is particularly suitable for remotely driven applications. The steering control on the operator's console has five positions labeled as follows:

Steer Left
Hold Left
Center
Hold Right
Steer Right

In either extreme, the steering motor drives the steering assembly right (or left) until the desired angle of turn is reached. The operator then places the steering control lever in one of the "hold" positions until the turn is completed. When he returns the steering knob to "center", a centering device on the vehicle automatically returns the steering assembly to its straight ahead position.

This manner of steering is of course quite different from the direct steering wheel control found in cars and trucks. It is exactly like the full-power steering control found on many heavy vehicles, such as power rollers and earth movers. It has proved easy to learn and quite workable in practice.

3.3 Handling

The handling and manipulation of objects by Mobot Mark I is accomplished by the arm assembly, which is shown in close-up in Figure 3. The Mark I arm has five degrees of freedom which have proved quite adequate for the relatively simple tasks required of it. The five motions which are available independently in each of the two arms are as follows:

1. Arm translate
2. Arm rotate
3. Arm raise and lower
4. Elbow rotate
5. Jaw open and close

The entire arm assembly is mounted upon the forklift mechanism which was included in the basic vehicle chassis. This mechanism enables one to lift the entire arm assembly 12 feet above the floor, or to lower it to floor level. The mast also tilts fore and aft. All these motions are controlled from the console and enable the operator to place objects held by the arms in many different locations.

Figure 4 shows several typical arm configurations indicating the variety of motions which can be accomplished even with this relatively simple arm geometry.

3.4 The Command System

The command system includes the cable which joins the control console to the Mobot, as well as the multiplexing units provided at either end of this cable. This cable must transmit the following items between the console and the Mobot: Electric power, command signals, two TV signals, one audio signal.

All of these items are transmitted through a single three-conductor cable using a multiplexing scheme described in the Appendix. To appreciate the effectiveness of the Mobot command system, it may be pointed out that over 55 independent control signals are transmitted through the system without interaction either among themselves or with the other information. Table II itemizes these control channels; a study of this table reveals the number and variety of motions and actions which can be controlled by the Mobot command system.

Each control channel is a digital "on-off" system which is compatible with the rate-command controls utilized on the Mobot itself. Thus the operator has to operate only two-position or three-position switches, which facilitates the layout of the console, as discussed further below. This system can accommodate even more command signals than are presently utilized. Additional control channels are inexpensive and can quickly and readily be added to handle any additional functions which may be desired.

The band width required by the command signals is comparable to that of a high-fidelity audio amplifier. Thus it is simple to use a radio link, rather than a cable, should this be required.

3.5 Power Systems

Mark I includes two electrical and two hydraulic power systems. The traction and steering system and the mast hydraulic system are 24 V DC. A storage battery provides for operation of the vehicle for several hours without AC power. A trickle charger maintains battery charge during normal operation.

Experience with this console has been quite satisfactory, although a somewhat smaller console with controls and instruments even more closely grouped would appear to be desirable for future developments.

The use of pistol-grip controls for the arms, with additional buttons and switches to supplement the basic motions of the grip as a whole, has proved acceptable to the operators. Future developments in Mobot controls will probably be in the direction of adding even more controls to the pistol-grips, as opposed to mounting controls on the separate panels. This reduces arm motion and increases finger motion, which appears to be preferred by most operators.

Learning the operation of the Mobot has proved not too difficult; it is comparable to a typewriter in complexity and learning time.

There seems to be almost no limit to the complexity of motions which can be learned and controlled by an experienced Mobot operator. One can even imagine future Mobots with two or three operators, each concerned with a separate portion of a very complex vehicle, and with a chief operator who coordinates the entire operation.

4. OPERATING EXPERIENCE

Mobot Mark I has been in service at the time of this writing for about 60 days. In this time several operators have had an opportunity to learn the machine, and it has been employed for a variety of tasks. Typical tasks include pouring a liquid from one cup to another, opening a cabinet door, placing an instrument on a table or shelf, removing a cover from a (simulated) radioactivity-storage well, and operation of power tools.

This experience has clearly demonstrated that it is completely practical to operate rapidly and accurately with the Mobot Mark I utilizing the TV vision system described above. Direct line-of-sight vision has proved not to be necessary and indeed to be deleterious to proper operation of the Mobot. This experience has also demonstrated the vehicle to be reliable and rugged so that one can with confidence depend upon it in operating in hot cells or other hazardous areas.

The complexity and learning time of the Mobot Mark I are comparable with those of a typewriter or musical instrument. With only a few minutes instruction, one can sit at the console and operate the machine slowly and clumsily. After some hours of practice the entire operation becomes rapid and dextrous. Most important, the conscious thinking out of each motion gradually disappears with practice and, as with all complex learning of this class, one completely loses awareness of the intervening mechanisms and "thinks like the machine". This is another way of stating that the original objective of the Mobot concept can be achieved in that the operator is subjectively within the hazardous area and performing the desired tasks even though he is physically outside of the area and is perfectly safe and comfortable.

5. <u>THE "NEW LOOK" IN HOT CELLS</u>

The availability of Mobots as proven workable devices makes possible a complete reconsideration of the layout of hot cells. Since the beginning of work with nuclear materials, hot cells have changed very little in their basic concept. They have been small -- in the vicinity of 8 feet square; vision has been accomplished by means of very thick glass or liquid windows; handling has been accomplished by mechanical devices, such as the familiar Mod. 8 master-slave manipulators.

Experience with the Mobot Mark I has demonstrated that line-of-sight vision between the operator and the operating area is not necessary and that remote control of complex motions can be accomplished over any desired distance. This indicates that hot cells can now be designed in which no windows are required and in which the floor plan is determined only by the work to be accomplished. Figure 7 shows a very schematic concept of such a hot cell. This schematic sketch is intended to bring out the fundamental points just noted. The operator of course can equally well be located at a considerable distance from the hot area; this is sometimes quite advantageous.

The cost of such a modern hot cell, as compared to the conventional type, is usually considerably less when one is designing a completely new facility. Adaptation of existing facilities to employ the Mobot concept is usually difficult; however, some portions of the concept can usefully be employed in these also.

Another valuable attribute of hot cells employing Mobots is the almost complete lack of any pre-determined commitment concerning their manner of use. Since the Mobot has complete flexibility, such hot cells can be adapted very readily to accomplish tasks which may be required in future but which cannot be detailed at the time a facility is designed. Since the life of a radiation facility is very long, this minimizing of obsolescence can be of genuine economic value.

6. A LOOK AT THE FUTURE

Mobot Mark I is the first complete vehicle to embody the Mobot concept in all its aspects. As noted above, operating experience with Mark I has been quite satisfying. This encourages one seriously to consider much more advanced vehicles to perform more complex operations, or to operate in other hazardous areas than nuclear hot cells. This section will briefly note a few of the many Mobot applications now under study.

Large Mobots to operate in rough terrain are quite feasible. The Mobot command system can be applied to any conventional off-road vehicle. Mobot arms and the Mobot vision system complete a versatile vehicle with which to enter a contaminated region. Such vehicles, of course, use radio control.

Small, simplified Mobots for use in the crowded interior of conventional hot cells can significantly increase the effectiveness of such cells.

Very small Mobots to enter extremely restricted areas, such as reactor beam holes, are completely feasible and are under engineering study. Such Mobots can replace the elaborate long-handled tools now employed in many reactor installations and will simultaneously improve the operator's ability to perform his required work and reduce his exposure to radiation.

For underwater use, Mobots can perform the same functions as deep-sea divers, but can perform them far better. Undersea Mobots will make possible the construction and operation of complex underwater installations for both military and commercial purposes.

Mobots in space can effectively replace the space-suited astronaut of science fiction, and will prove useful in assembling large space stations and in exploring the moon and planets.

On a more practical note, a Mobot firefighter can deliver water or chemicals to extinguish fires far more effectively and safely than can a human firefighter.

As briefly noted above, the Mobot command system is purely electronic in its operation. This suggests a new group of applications for computers. The combination of computers with Mobots has only begun to be explored. A few examples now under study include the use of a computer to cause a Mobot to repeat a pre-determined series of operations, and the use of a computer to convert the degrees of freedom built into the Mobot structure into rectangular or other geometrically simple coordinate systems.

The above paragraph notes two examples of computers as supplements to Mobot systems. It is interesting to speculate upon the opposite combination, namely, the use of a Mobot device as an output mechanism for a large computer. Presently, most large computers produce only columns of figures as their output. The availability of Mobots with their electronic command systems creates the interesting speculation of a computer which can accomplish physical work as well as merely produce technical data.

All of the advanced Mobots described above, and numerous others, are completely feasible applications of the Mobot concept. The successful operation of the Mark I Mobot has demonstrated the soundness of the concept. Engineering studies of many advanced Mobots and Mobot components are now proceeding actively.

TABLE I

MOBOT MARK I SPECIFICATIONS

Handling Arms (2)	3 feet long
Shoulder Rotation	360°
Shoulder Bend	30°
Elbow Bend	120°
Jaw Pressure	10 - 800 pounds
Mast	
Elevation	0 - 12 feet
Tilt	5° forward 10° backward
Over-all length (excluding arms and tail boom)	88 inches
Over-all width (with TV)	75 inches
(excluding TV)	38½ inches
Height (mast lowered)	83½ inches
(mast raised)	155 inches
Turning Radius	78 inches
Weight	4500 pounds
Cable Length	200 feet
Lift Capacity - Arm	150 pounds
- With Hook on Mast	1500 pounds

TABLE II

CONTROL CHANNEL ASSIGNMENT

Control Channel	Function	Control Channel	Function
1+	Left Arm Traverse Right	1-	Left Arm Traverse Left
2+	Left Shoulder Raise	2-	Left Shoulder Lower
3+	Left Shoulder Rotate Clockwise	3-	Left Shoulder Rotate Counter-clockwise
4+	Left Elbow Raise	4-	Left Elbow Lower
5+	Left Jaws Open	5-	Left Jaws Close
6+	Left Jaw Pressure Increase	6-	Left Jaw Pressure Decrease
7+	Right Arm Traverse Left	7-	Right Arm Traverse Right
8+	Right Shoulder Raise	8-	Right Shoulder Lower
9+	Right Shoulder Rotate Clockwise	9-	Right Shoulder Rotate Counter-clockwise
10+	Right Elbow Raise	10-	Right Elbow Lower
11+	Right Jaws Open	11-	Right Jaws Close
12+	Right Jaw Pressure Increase	12-	Right Jaw Pressure Decrease
13+	Left Camera Pan Left	13-	Left Camera Pan Right
14+	Left Camera Tilt Up	14-	Left Camera Tilt Down
15+	Right Camera Pan Left	15-	Right Camera Pan Right
16+	Right Camera Tilt Up	16-	Right Camera Tilt Down
17+	Left Camera Focus Near	17-	Left Camera Focus Far
18+	Right Camera Focus Near	18-	Right Camera Focus Far
19+	Trolley Move Left	19-	Trolley Move Right
20+	Ram Raise	20-	Ram Lower
21+	Ram Tilt Forward	21-	Ram Tilt Back
22+	Steer Left	22-	Steer Right
23+	Drive Forward	23-	Drive Reverse
24+	Spare	24-	Spare

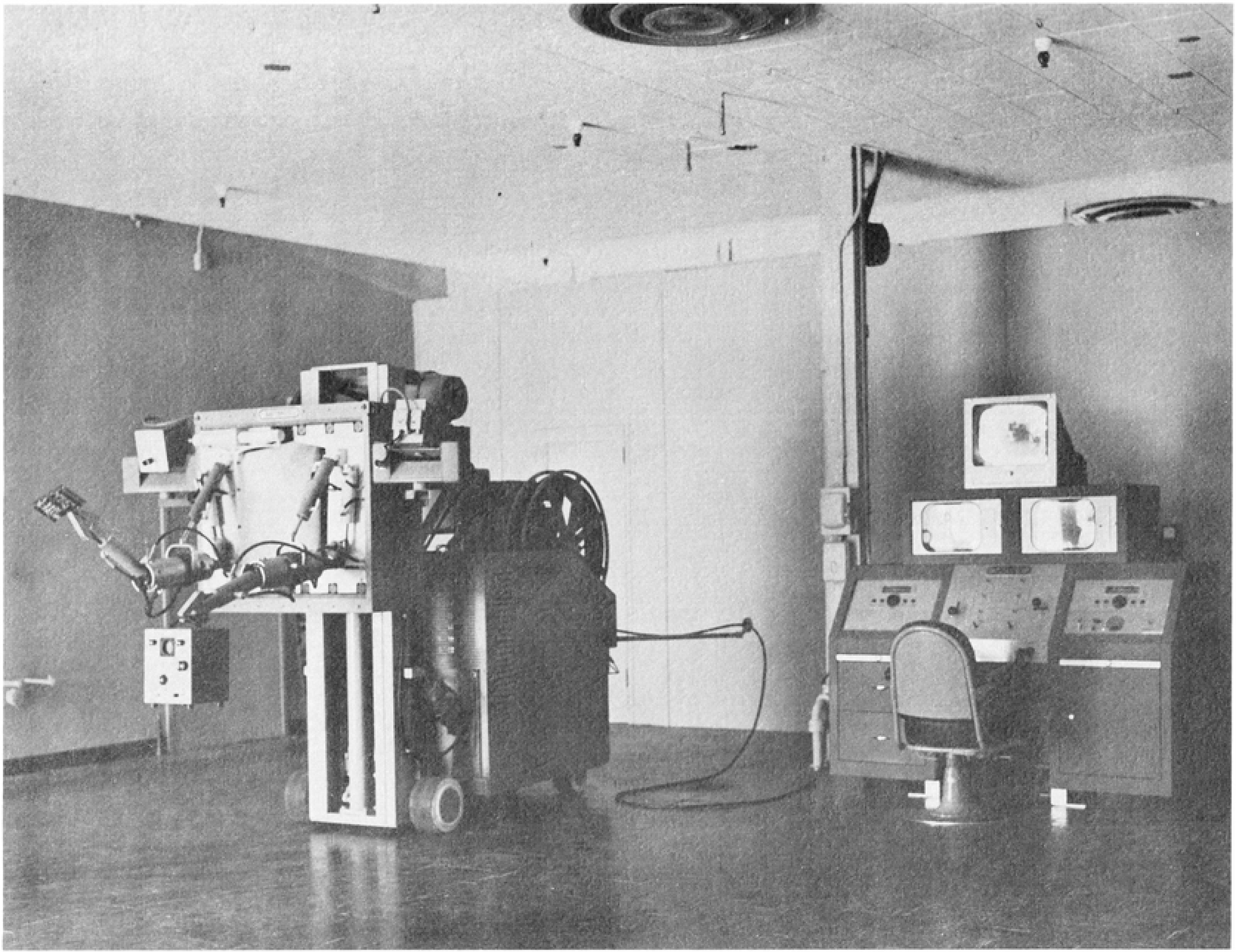

Figure 1

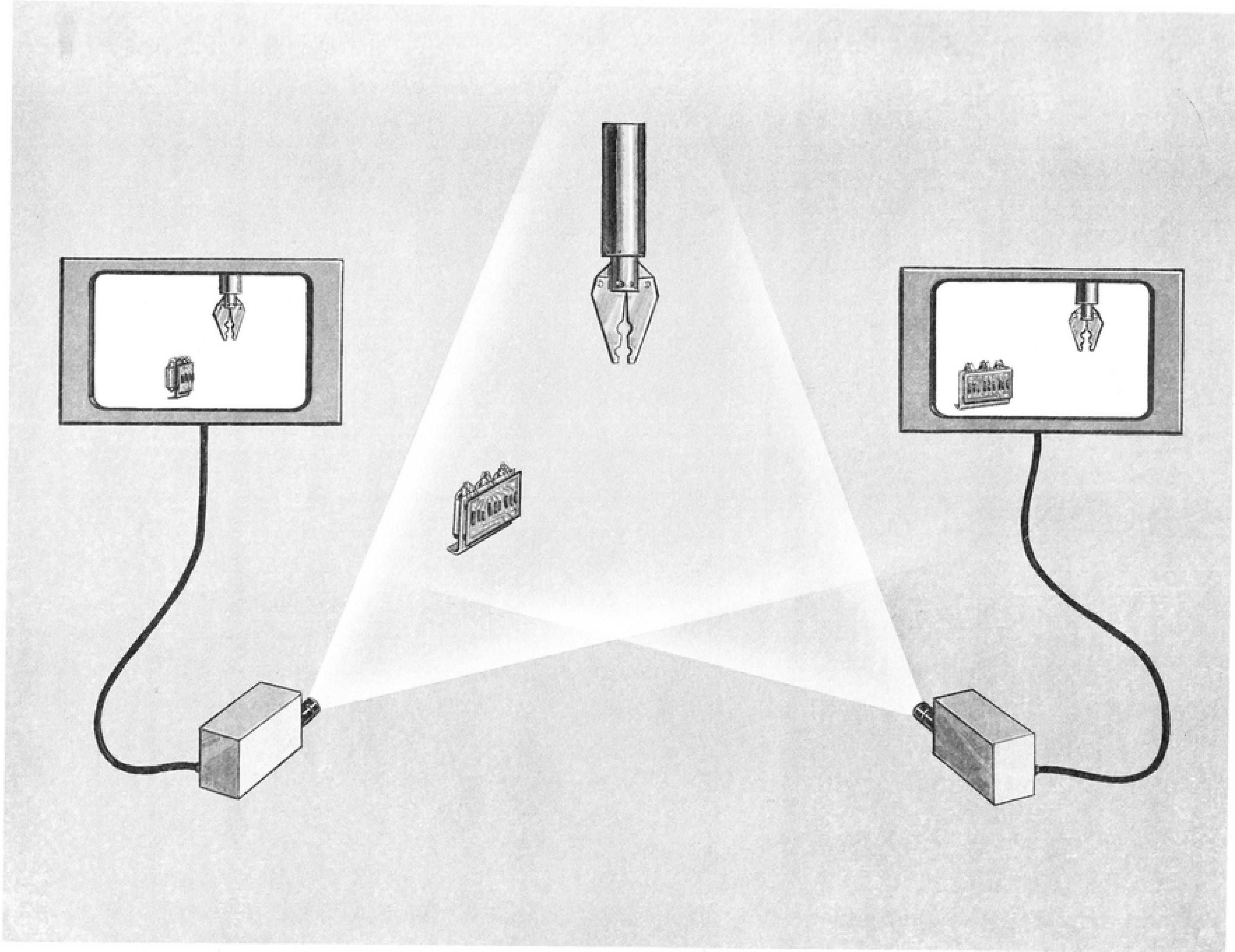

Figure 2

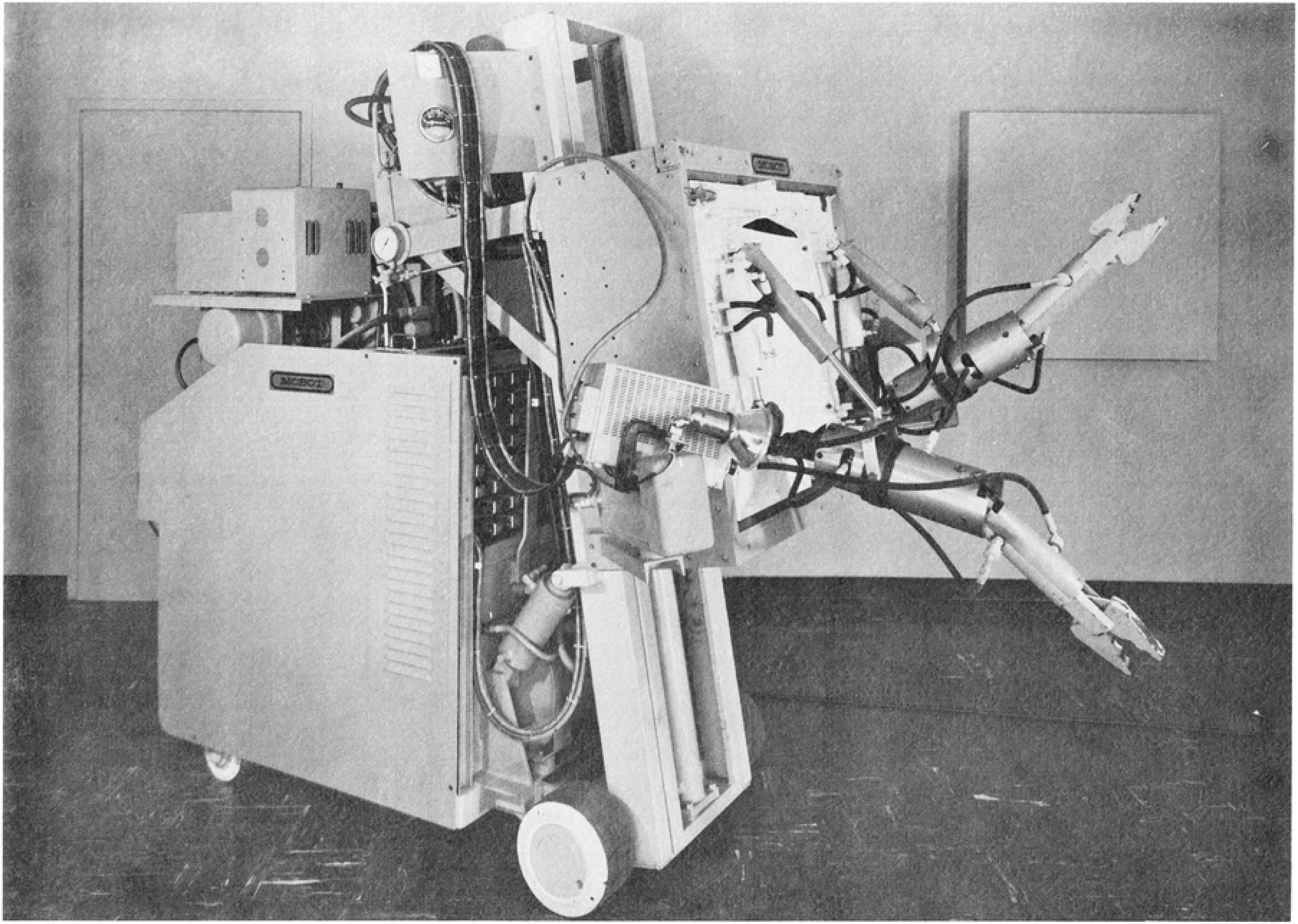

Figure 3

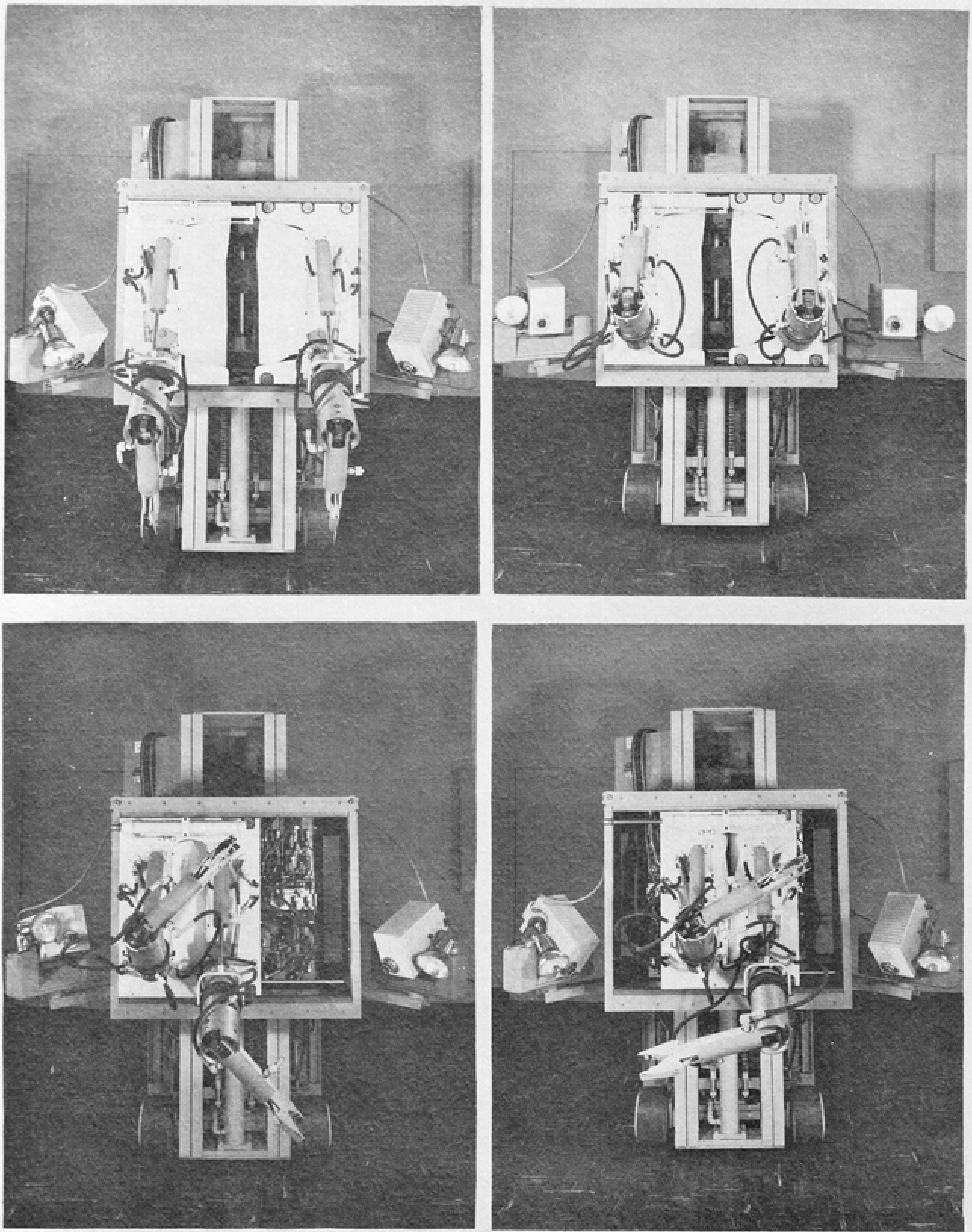

FIG. 4

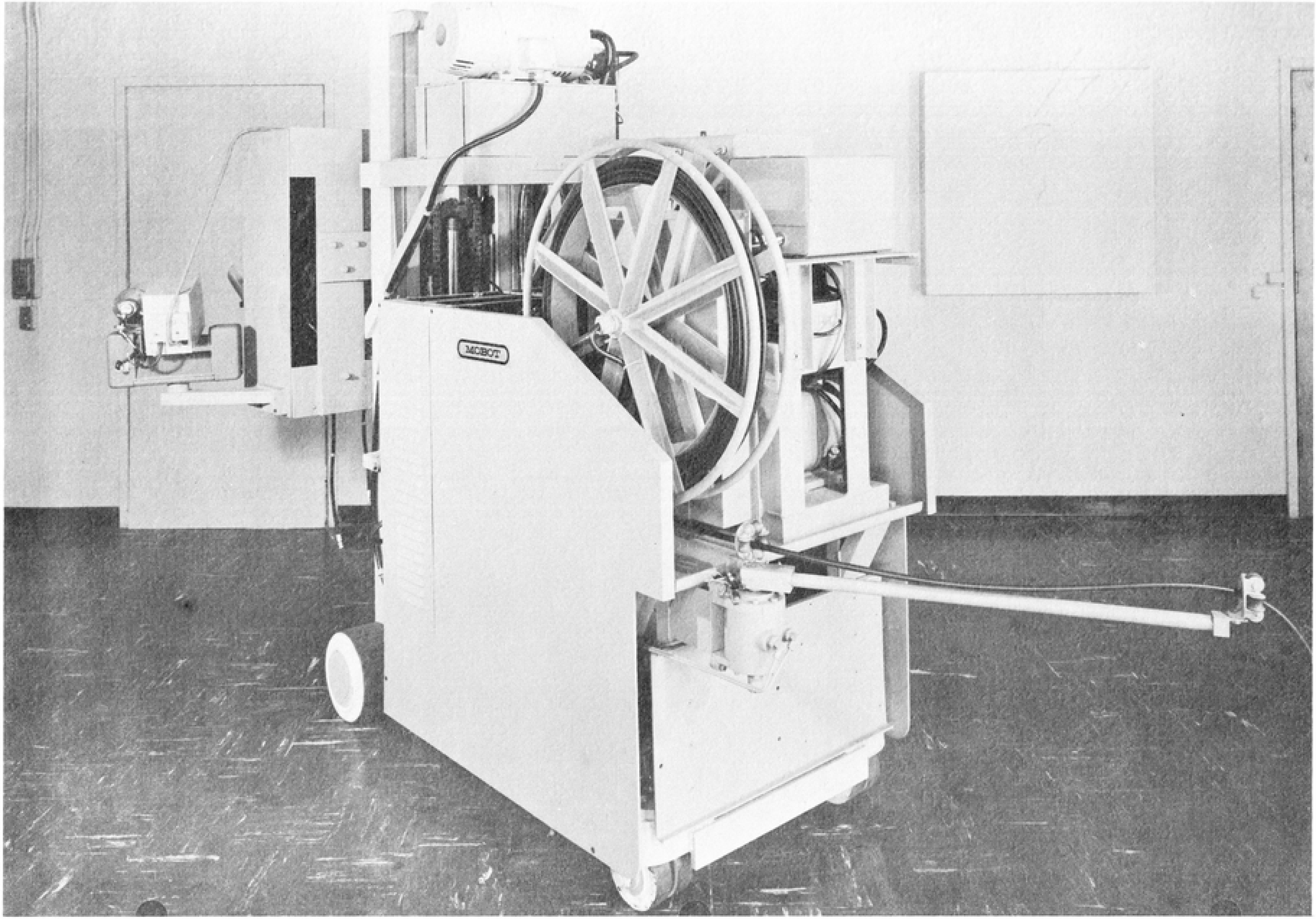

Figure 5

Figure 6

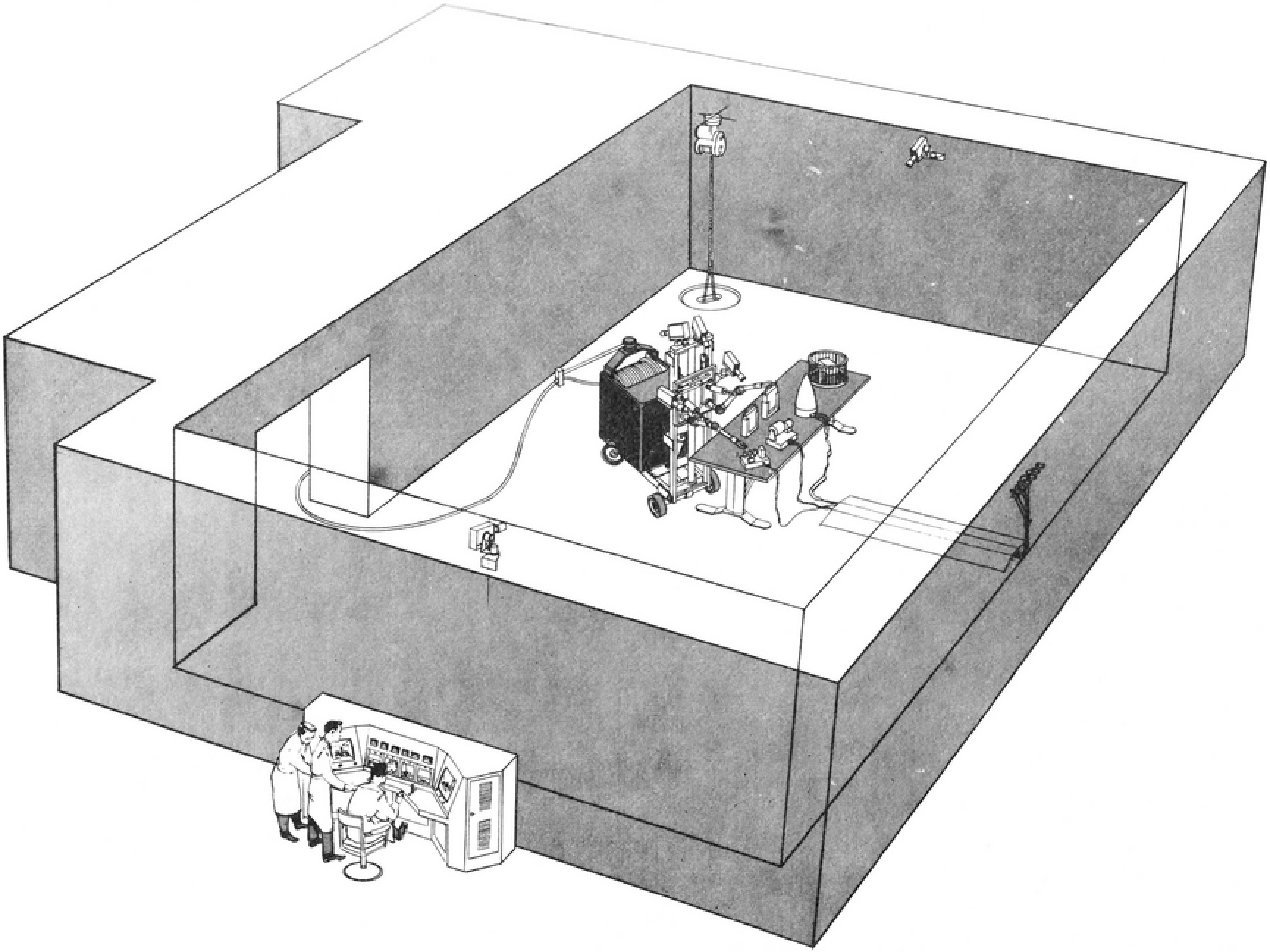

Figure 7

APPENDIX

MOBOT COMMAND SYSTEM

1. INTRODUCTION

The requirements for electronic control circuitry for remote handling devices are clearly exemplified in the command system of the Hughes Mark I Mobot.

The principal requirements are the following: A large number of channels, between 50 and 100, is required; the multiplexing scheme used must be compatible with either cable or radio link between control console and remote vehicle; data rate is rather low, being limited by human reaction time to about 0.1 second per individual control channel. For reasons having to do with simplicity in the handling mechanisms themselves, on-off controls were required for all the control functions.

The control system to be described meets the requirements briefly outlined above and is applicable to numerous other remote control problems where a multiplicity of functions must be operator-controlled over a considerable distance. A digital control system was selected, since this minimizes linearity requirements in the communication link and permits the use of synchronous commutating switches to accomplish the multiplexing function.

A single 3-conductor cable can readily accommodate the trains of pulses which carry the control information. This same cable conveys 60-cycle AC power to the vehicle and conveys two TV channels and one audio channel from the vehicle to the control console. These latter functions are separated from the control channels by rf carrier frequency discrimination.

2. ELEMENTS OF THE CONTROL SYSTEM

The basic components comprising the remote control system are shown in Figure A-1. When one of the control switches is closed, 45 volts is applied to a contact on the local commutating switch. The commutating switches are synchronized so that corresponding contacts are sampled simultaneously. Therefore, while the energized contact is being sampled, a voltage pulse will appear at the corresponding contact of the remote commutating switch. The remote switching circuit is designed to accept the train of pulses from the switch contact and produce a continuous relay closure so long as the train continues. The relay can be used to operate any function which requires only on-off control.

It was found that by using a 45-volt battery to supply the control pulses, a very simple remote switching circuit was required. The power which can be transmitted through the commutating switches to the remote switching circuits is principally limited by the capacitance of the interconnecting cable. A 270-ohm resistor is connected in series with the cable at each end to limit the cable-charging current which must be carried by the commutating switch contacts. A 10K resistor is connected in parallel with the cable at each end to discharge the cable between contacts. If the 10K resistors were omitted, the operation of one control channel would cause spurious operation of several succeeding channels because of the charge stored in the cable capacitance. Thus, most of the power supplied by the 45-volt battery is used to charge the cable capacitance.

For the Hughes Mark I Mobot, a triaxial interconnecting cable 220 feet long was used to permit transmission of 60-cycle power as well as control and television signals. The 60-cycle power is used to operate the motors driving the commutating switches as well as many other units on the Mobot vehicle. Since the outer grounded shield of the triaxial cable is used in common by the power and control signals, the drop in the 60-cycle voltage along this conductor appears as an ac component on the control pulses. The control pulse amplitude must be large compared to this ac component; therefore, in this application a practical lower limit to the control pulse amplitude is set by the required 60-cycle power transmission.

The 54 contact commutating switches used for this project were previously developed by Hughes Aircraft Company for another application. Although break-before-make operation is used, the ratio of contact to inter-contact time is over 0.8. The minimum speed of rotation of the commutating switches is determined by the required response time of the control channels. It is necessary that the sampling frequency for each channel be greater than the reciprocal of the response time. For this application it was desired to have a response time of the order of 0.1 second, so a sampling frequency of 30 per second was chosen. This corresponds to a rotational speed of 1800 rpm for the rotary commutating switches.

3. REMOTE SWITCHING CIRCUITS

The remote switching circuits must accept a train of pulses having a duration of about 500 microseconds with a repetition rate of 30 per second, and produce a relay closure by the time the third pulse occurs. The relay must then remain actuated so long as the pulse train continues, and it must open within 0.1 second of the conclusion of the pulse train. The circuit which was developed to meet these specifications requires only one double triode vacuum tube and one relay per channel.

Since the number of control channels required exceeded the number of contacts on the commutating switches, a method was sought for utilizing a contact to control more than one function without loss of response time. This was accomplished by connecting a circuit sensitive to positive pulses and another sensitive to negative pulses to a contact, so that two control channels may operate through one contact. Fortunately, a majority of the desired operations involved opposing motions, such as drive forward, drive reverse; steer right, steer left; and tilt forward, tilt back. Since simultaneous operation of these opposing motions is never desired, control of the two functions via a common contact is possible with no loss of flexibility or response time. Figure A-2 shows the remote switching circuits developed for positive and negative inputs. All functions which may require independent operation are connected to positive input circuits only.

The operation of the remote switching circuits is as follows. The left-hand triode in the positive input circuit is connected as a diode detector with a time constant of 0.1 second so an appreciable charge is held between pulses. This positive voltage is applied directly to the grid of the normally cut off right-hand triode producing conduction and operation of the relay. The circuit values are chosen so that actuation and de-actuation times for the relay are almost identical. The left-hand triode of the negative input circuit is also connected as a diode detector. In this circuit, however, the right-hand triode has much higher gain because of the small cathode resistor and only a portion of the input signal is applied to its grid to cut off the normally conducting triode. In this circuit the relay switches from its closed to its open position when an input signal is received.

4. INITIAL SWITCH ORIENTATION

A fundamental requirement of the time-sharing multiplex control system described above is that the commutating switches be accurately synchronized. The angular error between the two switch rotors should be less than one degree. Using synchronous motors with the same rated speed to drive the switch rotors, it is easy to attain equal rotational velocities. The rotors can be adjusted to sample corresponding contacts on the two switches simultaneously by rotating the stator of one motor on its axis while both motors are driving the switches at synchronous speed. Synchronism can be checked by observing the rotors side by side using a stroboscope. For a more exact method of detecting synchronism, a voltage source is connected to a contact of one switch and a load resistor is connected to the corresponding contact of the other switch. If the switch rotors are interconnected, a voltage pulse can be observed across the load resistor at synchronism using a triggered oscilloscope. A very accurate adjustment can be made by manually rotating the motor housing to achieve maximum pulse duration as observed on the synchroscope.

If reluctance synchronous motors are used to drive the switch rotors and the motor frames are clamped in the positions found above, these positions will require no further adjustment. This is because of the ability of reluctance synchronous motors to synchronize at fixed angular positions. A four-pole motor which runs at 1800 rpm will phase in one of four positions, 0°, 90°, 180°, and 270° apart. If one motor is allowed to run continuously and the other is turned on and off periodically because of the random choice of phasing positions, eventually the second motor will drop into its properly synchronized position found above. This method for achieving synchronism was not considered to be satisfactory, however, and the following method was developed for automatically accomplishing the task.

5. AUTOMATIC SYNCHRONIZING CIRCUIT

The automatic synchronizing circuit consists of a motor interruptor circuit and a synchronism sensing circuit. These circuits are shown in Figure A-3. The motor interruptor circuit uses a 2D21 thyratron as a relaxation oscillator. The capacitor in the plate circuit of the 2D21 charges through the large series resistor until the breakdown voltage of the thyratron is reached. At this point, the capacitor is discharged through the tube and relay coil. The tube again becomes cut off and the cycle repeats. The surge of current through the relay coil during the capacitor discharge causes the contacts to open momentarily. Through these contacts, the motor driving the local commutating switch receives its power. The time constants in the circuit are adjusted so the motor will drop back only 90° with respect to the motor driving the remote commutating switch each time the relay is pulsed. Depending on the initial phase difference between the two rotors, up to 3 interruptions of power to the local motor will be required to drop the switches into synchronism. When this condition is reached, the synchronism sensing circuit operates to disable the interruptor circuit.

The synchronism sensing circuit as shown in Figure A-3 is identical with the remote switching circuits previously described which are sensitive to positive input pulses. One contact on each commutating switch is required for the synchronizing circuit. A 45-volt battery is connected to this contact on the remote switch and the synchronism sensing circuit is connected to the corresponding contact on the local commutating switch. When synchronism is attained, the sensing circuit operates to close the relay in its plate circuit, thus disconnecting the plate voltage from the interruptor circuit. These simple circuits will automatically bring the two commutating switches into accurate synchronism within a few seconds, once the initial orientation has been accomplished.

6. SUMMARY

A time-sharing multiplex system for remote control has been described. Two high speed rotary commutating switches operating in synchronism are used to permit many remote functions to be turned on and off using only two interconnecting conductors. If the commutating switches have n contacts, up to 2(n-1) separate control channels are possible using the polarity sensitive remote switching circuits described. One contact is used for the automatic synchronizing circuit which brings the two switches into accurate synchronism within a few seconds. The remote switching circuits are simple and inexpensive. Only one vacuum tube and one sensitive relay are required for each channel.

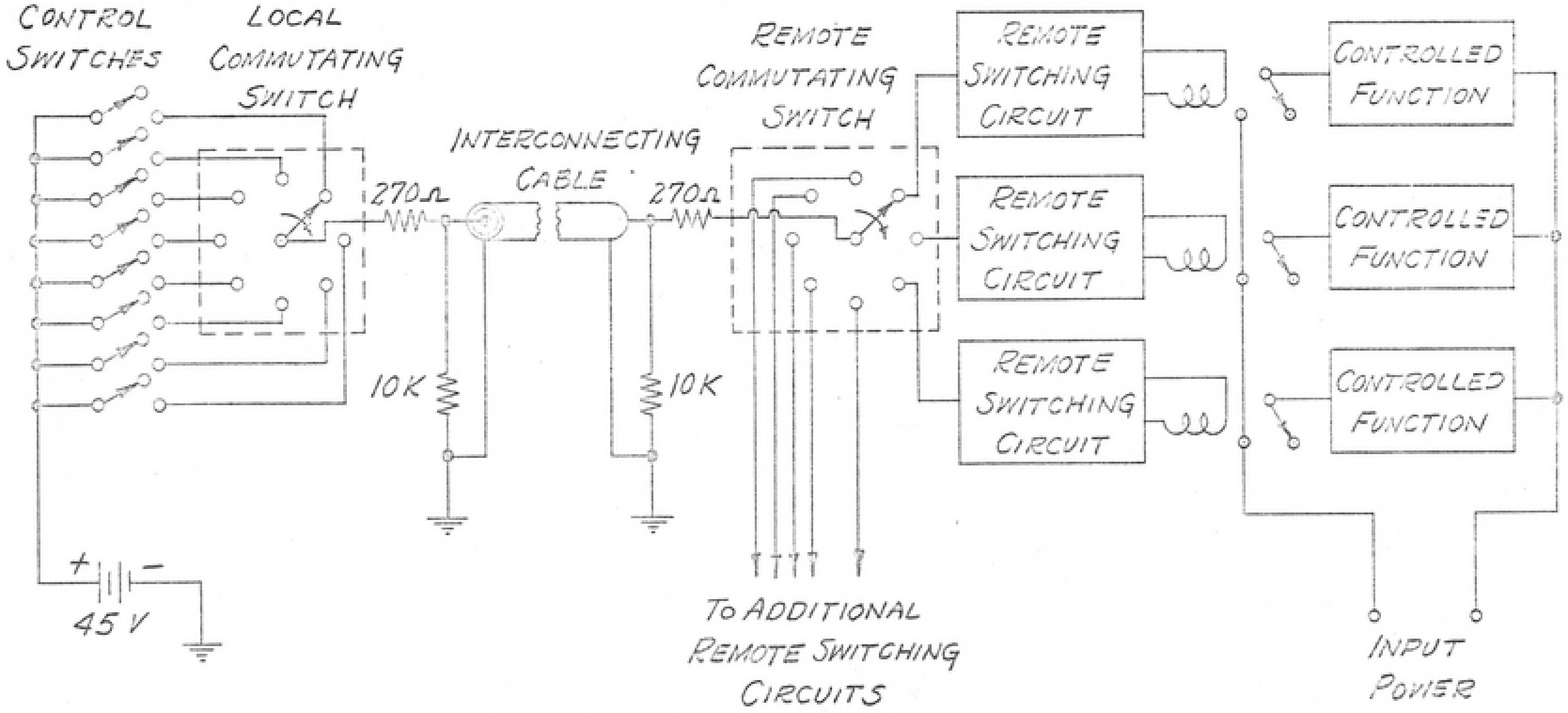

FIG. A-1 ELEMENTS OF THE REMOTE CONTROL SYSTEM

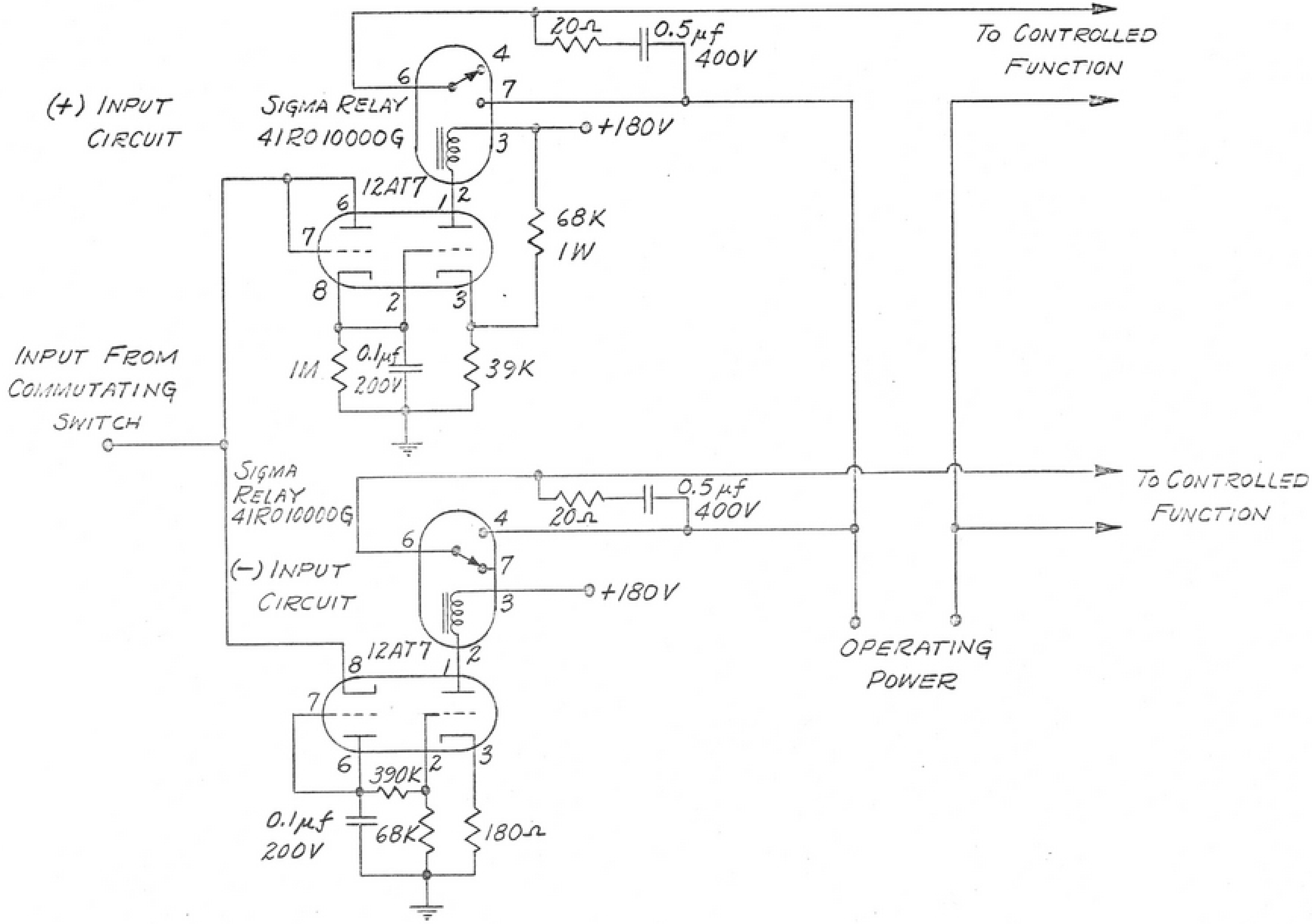

FIG. A-2 POLARITY SENSITIVE REMOTE SWITCHING CIRCUITS

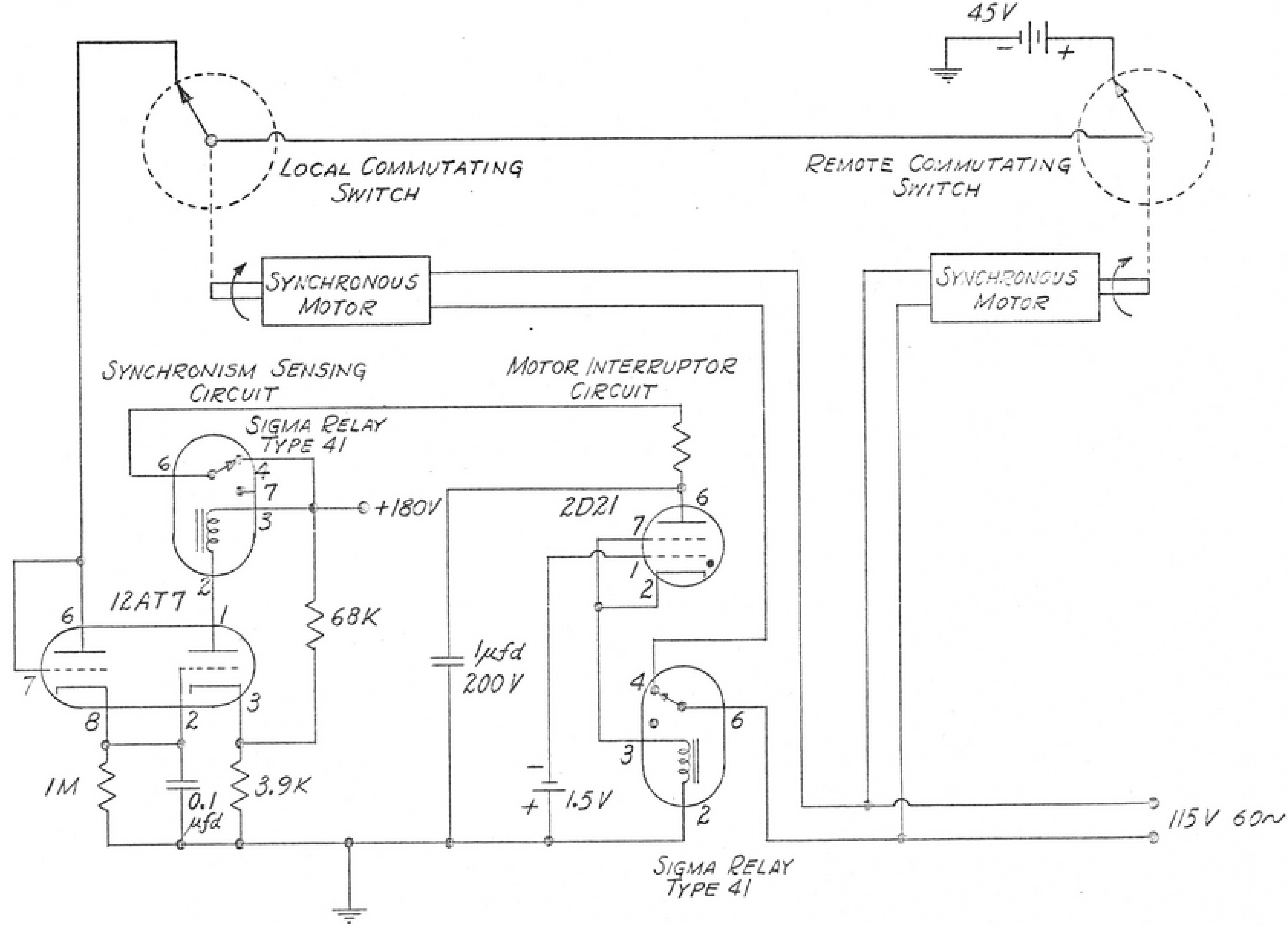

FIG. A-3 THE AUTOMATIC SYNCHRONIZING CIRCUIT