FOREWORD

This survey was conducted by the Maintenance Design Section, Human Engineering Branch, Behavioral Sciences Laboratory, 6570th Aerospace Medical Research Laboratories, between October 1960 and March 1961. The work was done in support of Project No. 7184, "Human Factors in Advanced Flight," Task No. 718406, "Design Criteria for Ease of Maintenance." Lt. D. Frederick Baker compiled this report. Grateful appreciation is extended to the companies, identified by contribution, who furnished material for this publication.

ABSTRACT

A survey of industrial opinion on remote handling in space was undertaken to document early concepts and to identify areas of agreement, areas of conflict, and unique ideas relating to the subject. Seven industrial concerns and one military agency provided papers on the role of remote handling in space. These papers are discussed in terms of: (a) remote operations of which there are five major categories—maintenance, assembly, experimentation, transfer operations, and emergency operations; (b) space vehicle design—the manned lightweight capsule, with anthropomorphic gloves, stabilization arms, window ports, and two to three manipulator arms, being representative; (c) manipulator design—concerning actuation, configuration, control, and feedback systems; and (d) space environment factors—vision, weightlessness, temperature fluctuations, high-energy radiation, and micrometeorite collisions.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

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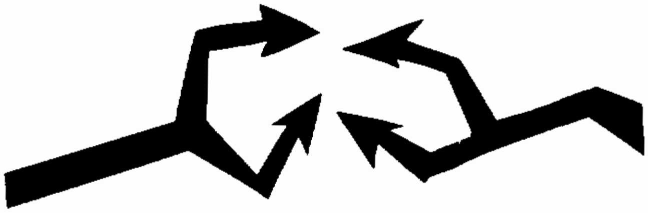
survey of remote handling in space



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BACKGROUND DATA

Man's interest in and knowledge of space and space travel are accelerating. As unique aspects of space operations are identified, special interest is directed toward solution of the problems they pose. One problem relates to the need for a remote-handling capability in space. This need has been specified by many people, especially members of the aerospace industry. In this publication, the views of several of them are compiled.

In October 1960, a letter was sent to several concerns which had previously demonstrated an interest in this area. A brief on the role of remote handling in space was solicited. In addition to the general subject of remote handling in space and related tasks, problems relating to visual access, control actuations, and design characteristics necessary in space applications were mentioned as examples of topics of interest. Material was solicited with the intention that it be only that information which had been the result of prior effort on the part of each company.

The companies who participated in this project are: Bell Aerosystems Company, Douglas Aircraft Company, Inc., General Electric Company, General Mills, Inc., Hughes Aircraft Company, Lockheed Aircraft Corporation, and Norair Division of Northrop Corporation. In addition, the Maintenance Design Section, Human Engineering Branch, Behavioral Sciences Laboratory, has contributed a section.

This publication presents these early concepts so that areas of agreement, possible areas of conflict, and unique ideas can be identified. There is, of course, replication in ideas and treatment of subject.

DISCUSSION

The contents of the eight papers which comprise this survey may be discussed in terms of: (a) remote operations, (b) space vehicle design, (c) manipulator design, and (d) space environment factors. Remote operations are considered first: identifying space tasks for which remote handling is indicated serves as the basis for identifying other major problem areas of space vehicle design, manipulator design, and space environment.

Remote Operations

Determining representative remote operations in space is of major concern to most of the participants in this survey. Five main operations categories are identified:

a. Maintenance (mentioned in every paper)—including inspection, repair, servicing, and checkout

b. Assembly and disassembly of space stations—including grappling, docking, and mating between vehicles or subassembly sections, and construction or destruction of lunar (or planet) base facilities

c. Experimentation—including exploration, sampling, and testing

d. Transfer of personnel and loading and unloading of supplies and equipment

e. Emergency operations—including escape and rescue

This list includes every operation mentioned in the papers. It is significant that most of the contributions are similar in their organization of remote-handling operations in space. The limited number of operation categories reflects the orderly and realistic approach to defining remote operations.

These remote operations must be considered in terms of both the remote-handling equipment used to accomplish these operations and the equipment and tools dealt with or handled by the remote-handling manipulator itself. Norair points this out in saying: "One of the major human engineering problem areas to be investigated lies in the integration of a man-manipulator subsystem with the equipment on which it will be used."

Space Vehicle Design

"Designs proposed for biologically protective space support units to be used in extra-vehicular operations indicate: (a) that the units may by anthropomorphic, nonanthropomorphic, or somewhere between, and (b) that the importance of remote-handling systems increases with progress along the continuum toward the nonanthropomorphic version." This account of remote handling and its relation to vehicle design was taken from the Behavioral Sciences Laboratory paper. It serves as a reference in discussing the vehicle design concepts of the other papers.

The lightweight capsule, described in five papers, belongs somewhere between anthropomorphic and nonanthropomorphic units, since it includes elements such as a hard shell conforming to the approximate shape of the human operator, and both manipulator arms and (in some cases) special anthropomorphic gloves. Table I (by no means complete) shows how five companies compare in their concepts of lightweight capsules.

TABLE I

LIGHTWEIGHT CAPSULE DESIGN

Lightweight Capsule	Anthropomorphic Glove Designs	Manned	Tethered	Stabilization Arms	Window Ports for Direct Viewing	Number of Manipulator Arms
Bell		X	X	X	X	2
Lockheed	X	X		X	X	2
Douglas	X	X			X	3
General Electric		X			X	2
Norair	X	X	X	X	X	3

The design concept presented by Bell suggests use of a small, buoy-shaped capsule. The Lockheed design is very similar. Lockheed describes its concept as being a small, lightweight, encapsulating vehicle to be used in lieu of space suits (which they feel will not be practical). According to Lockheed, "the best vehicle systems will result from a philosophy which minimizes vehicle mass." The "Humpty Dumpty Capsule" of Douglas' is similar to both the Bell and Lockheed concepts. However, the Bell system differs by addition of a tether cable and a command and data links system. The Norair lightweight capsule also has a power, intercom, and air umbilical to the mother-ship. The General Electric concept does not include tethering and is similar to the other concepts only in basic design principles of a minimum-mass, manned capsule.

Because of the particular interest of General Mills and Hughes in remote-handling equipment, they limit their discussions to nonanthropomorphic space tugs. The Hughes vehicle differs from the General Mills vehicle in that it is unmanned and tethered. As can be seen in figure 1, page 24, the General Mills manipulator arms fold into the manned space tug in a manner similar to that of the Behavioral Sciences Laboratory concept shown in figure 2, page 9.

Very simple remote-handling systems for space operations are visualized at this point. Some of the features are:

a. Lightweight capsule concept——The lightweight capsule combines the advantage of maneuverability (without many disadvantages of space suits) with the more rugged handling capacity of manipulators. The capsule would be positioned by means of reaction jet nozzles. The operator will operate the positioning jets as well as the remote-handling equipment. Bell Aircraft suggests that the operator will orient the positioning jets by means of a foot treadle.

b. Anthropomorphic gloves——Four out of the five lightweight capsules discussed have anthropomorphic glove designs. These capsules are obviously expected to work in close proximity to the task.

c. Window ports——All five of the capsules have window ports for direct visual access.

d. Stabilization arms——Three companies (Norair, Bell, and Lockheed) include suggestions for use of attachment arms to stabilize the capsule in working position at an orbiting satellite or space station. The multi-armed Hughes mobot also employs arms to fasten itself to the particular object on which it is working.

Manipulator Design

The present state-or-the-art for manipulators does not permit an extensive treatment of the subject of manipulator design. Present-day manipulators have been designed for use in hot laboratories, though there are certain design characteristics applicable to space vehicle operations. These are discussed below. Present use of "gloved boxes" for "low level" work has resulted in the widespread use of anthropomorphic gloves which are built right into the box. Problems related to these gloves in space operations have never been studied, but they are primarily sealing, durability of material, degree of tactile feedback afforded the operator, etc. These problem areas will be even more critical if anthropomorphic gloves are used to the extent which has been suggested. Problems in the design of manipulators are even more complex. Several areas must be analyzed:

a. Actuation——In the Norair paper, electrical actuation is listed as the type for space operations. The Behavioral Sciences Laboratory states that "because of the sealing problem, electrical or electronic linkage is preferred over mechanical linkage for manipulators." Advancements in the development of hermetically sealed mechanical drives may permit the use of electromechanical manipulators. Problems of hydraulic actuation (the fluid must be kept under constant pressure, thus requiring leakproof sealing, and it cannot be pumped by air or gas under zero gravity, thus requiring positive mechanical pressure) tend to discourage the use of hydraulic or electrohydraulic manipulators. General Electric suggests the use of hot gas or pneumatic actuation, but the problems related to hydraulic actuation would also discourage use of hot gas or pneumatic actuation.

b. Configuration—Hughes presents a design (see figure 1, page 29) described as not being "the ultimate arm design, but...indicative of a general-purpose arm capable of handling a wide variety of manipulative requirements." A shoulder-elbow-wrist configuration has been very popular. The Hughes design is representative of this configuration, and, in addition, has the significant feature of a completely self-contained arm. Maintenance of the actual manipulator arm is thus facilitated by interchangeable limbs. If a malfunction should occur in the manipulator arm, it can be removed for repair in a more advantageous maintenance environment. In the meantime, a spare arm can be plugged in.

A very important manipulator design problem is discussed in the Norair report. Existing manipulators have been designed to duplicate the physical characteristics of the human. By a re-emphasis on "designing system components for manipulator handling rather than manned handling, the limits of the anthropomorphic approach are removed." Thus, the ultimate manipulator arm configuration will probably reflect this philosophy: the arm will not necessarily resemble the human arm. This philosophy might be especially evident in corresponding design for controls. A few controls have been designed so that the operator has glovelike controls which effect corresponding motion in the master arm. This often results in unnecessary limitation of movement on the part of the operator. Nonanthropomorphic controls may in many instances free the operator of these limitations.

c. Control—The discussion of control of remote-handling devices is concerned primarily with configuration and with the type of control command system used. A recent study (ref. 1) indicated that body members other than the hands and arms can be efficiently used to control or dictate corresponding slave hand and arm motion. A control configuration involving foot pedals is an example. Several companies have been concerned with the type of command system to be used with remote-handling equipment. General Mills states: "At least for first applications, it appears that the rate type of control is best." The problem of control is touched on in the Behavioral Sciences Laboratory paper which concludes that, because of the limitations of space cabin room, displacement controls (to effect corresponding slave motion) should not be employed. A study by Birmingham and Taylor (ref. 2) on control systems treats the problem of pressure versus displacement control in much greater detail but arrives at the same conclusion: "With a moving joystick, the feedback pattern contains information about the displacement as well as stretch and pressure specifications. This might lead one to conclude that control with a pressure stick would be less accurate than with a joystick which moved. But quite the opposite conclusion has been reached by Gibbs [see footnote] who adduces physiological evidence to show that the proprioceptive information available during pressure control is greater than that arising from the manipulation of a displacement control."

d. Feedback systems—Any discussion of remote-handling equipment must cover the problem of visual access. Direct viewing is simplest, of course. A direct window port is described as part of the lightweight capsule concept. There are certainly many problems, however, such as glare and reflection, associated with monitoring a task through a window port. These problems seem unimportant compared to problems of indirect visual access via closed-circuit television (i.e., focusing, light, movement relationships, etc.).

Norair puts special emphasis on visual feedback as having to be in three dimensions. Stereotelevision offers perhaps the ultimate solution to the problem of information feedback for remote handling in space. Certainly, many companies feel that vision is the most important of the remote-handling feedback senses. The Bell paper describes kinesthetic and tactual cues as "second-order cues" which "may or may not be proportional to the original cues." In lieu of using these cues as we normally think of them, Norair suggests "using an auditory feedback which gives an indirect indication of texture and temperature."

Gibbs, C.B., The Continuous Regulation of Skilled Response by Kinæsthetic Feedback, A.P.U. 190/53, Great Britain Medical Research Council, March 1953.

Space Environment

Other than in the areas of vision and weightlessness, the reports which comprise this study consider the unusual environment of space as posing no more than a minor problem for remote handling. The visual problems are: empty field myopia, unstructured visual field, intense glare, unidirectional illumination producing extreme contrasts, and fluctuations between brightness and darkness. Each of these must be studied in detail. Some of the problems, especially the latter three, can be handled through the engineering and optical approach to a television system. In less sophisticated systems, in which direct viewing is advantageous, the use of sunshades and special filtering glass can be considered.

A highly publicized environmental problem is weightlessness. A representative view on this problem is contained in the Behavioral Sciences Laboratory paper which describes a solution to the problem in terms of "producing a closed force system" which "will require at least one manipulator appendage for holding equipment while work is being performed upon it by another." The ramifications of a gravity-free environment are discussed by the Hughes Aircraft Company in terms of acceleration and the fact that "a relatively small system of limited power consumption can direct the motions of quite heavy objects if appropriate consideration is given to their inertia." In some respects, then, the design of both manipulator and power source for the space environment may be simplified.

Other environmental considerations are advanced in the General Mills paper. Extreme temperature fluctuations can be controlled effectively by careful selection of components and materials and by proper design——in other words, knowing and understanding the problem of temperature extremes makes correction possible by rather conventional means. High-energy radiation and micrometeorite collision do not pose serious problems.

In this brief discussion, the emphasis has been on general design characteristics which can serve as guides to further thinking on the problems of remote-handling applications in space systems. While each of these first-generation designs for remote handling in space may have compelling features, we should not come to definite conclusions until further analysis and pertinent research can be performed.

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INTRODUCTION

Research and development efforts are being directed toward exploitation of the environment beyond the atmosphere of our planet. This environment, space, is characterized by low pressure, lack of oxygen, increased amounts of solar radiation, cosmic rays, and meteors. Hence, it is hazardous to man. Nevertheless, man's entry into space is believed necessary to achieve the reliability and versatility required for effective space expeditions. Because of the quantity and severity of risks to health, man will probably not be able to accomplish extra-vehicular work in space without means of extending his mental and physical skills beyond a considerable amount of protective shielding.

Designs proposed for biologically protective space support units to be used in extra-vehicular operations indicate: (a) that the units may be anthropomorphic, nonanthropomorphic, or somewhere between, and (b) that the importance of remote-handling systems increases with progress along the continuum toward the nonanthropomorphic version. The anthropomorphic version is similar in design to the pressure suit now used for high-altitude flying. Its feasibility depends upon the duration and location of the space operation. A suit such as this used in conjunction with a nonanthropomorphic unit or "space tug" equipped with a remote-handling system appears desirable.

SPACE SUPPORT UNITS

Two classes of space tugs have been conceived, manned and unmanned, both equipped with remote-handling and sensory-feedback facilities. Each type has advantages and disadvantages. The unmanned support unit, electronically linked to its control station, could cover a relatively large area for long periods without life support equipment. On the other hand, man's decision-making and trouble-shooting abilities would be directly available in the manned unit, and the manned system would probably be more versatile in task performance capabilities (see figure 1).

The ingenuity of remote-handling equipment engineers is challenged anew by space support system recommendations such as: (a) man should leave the space cabin only when equipment alone cannot perform the function; and (b) design should be such that the support unit will perform as many operations as possible. The creative burden is thus placed on the designers of manipulator support units.

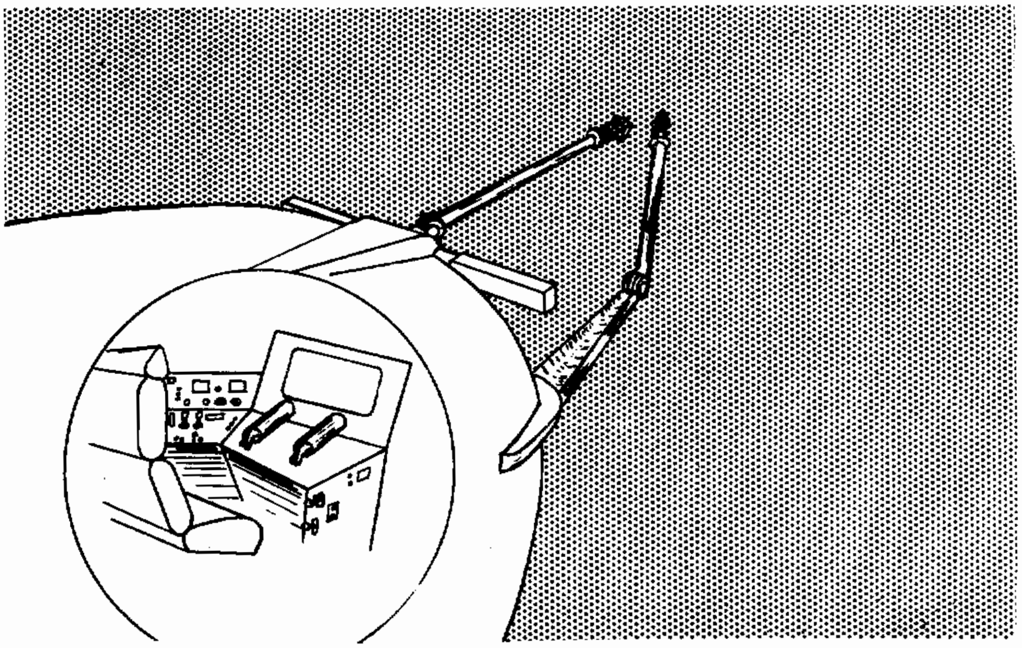

Figure 1. Artist's Concept of Control Console and Slave Arms of Manned Space Vehicle with Electronic Control and Closed-Circuit Stereotelevision

The tasks for remote handling in space are similar to those involved in ground operations. Among them are assembly, disassembly, and maintenance of space stations, auxiliary space units, and vehicles. Such tasks will involve the alignment and positioning of components and fasteners. Because of difficulties related to the gravity-free characteristic of space, fasteners should be designed so that operative forces will be equal and opposite in vector. Similarly, tasks such as refueling and transfer of supplies and equipment must also be given special consideration in the design of space support equipment. Automatic handling devices may be feasible for such operations. Many of the problems and recommendations discussed in connection with task analyses, equipment design, and training programs for effective remote handling will apply, but the unique characteristics of space must not be neglected. The most highly publicized of these is weightlessness. Principles derived from investigations of the use of hand tools under frictionless conditions should have applications for remote-handling design (ref. 1). For example, producing a closed force system will require at least one manipulator appendage for holding equipment while work is being performed upon it by another. Thus, in the tractionless state which exists with weightlessness, the workman will be able to perform his task by applying forces against the separate limbs of the manipulator while maintaining constant orientation toward the task.

Tools or manipulator hand accessories which fasten to the equipment being assembled or disassembled are recommended to eliminate continual application of contact force and minimize the number of manipulator appendages required. Optimal design of equipment to be handled and interchangeable, special-purpose jaws and tools should also contribute to attaining the latter goal. When equipment is designed so that it cannot easily be grasped and handled by manipulator hands, a controlled magnetic field in the manipulator appendage could be useful. A general-purpose appendage to accommodate interchangeable, special-purpose end units for welding, cutting, lighting, etc., might be desirable.

A concept for maintenance of the manipulator arms is based on a design in which the arms retract into the space vehicle. In figure 2, the arm, forearm, and hand sections fold into the extender which retracts into the vehicle. An auxiliary mechanical retraction device would be desirable in case of failure of the electrical retraction system, assuming the manipulator is electromechanical in design.

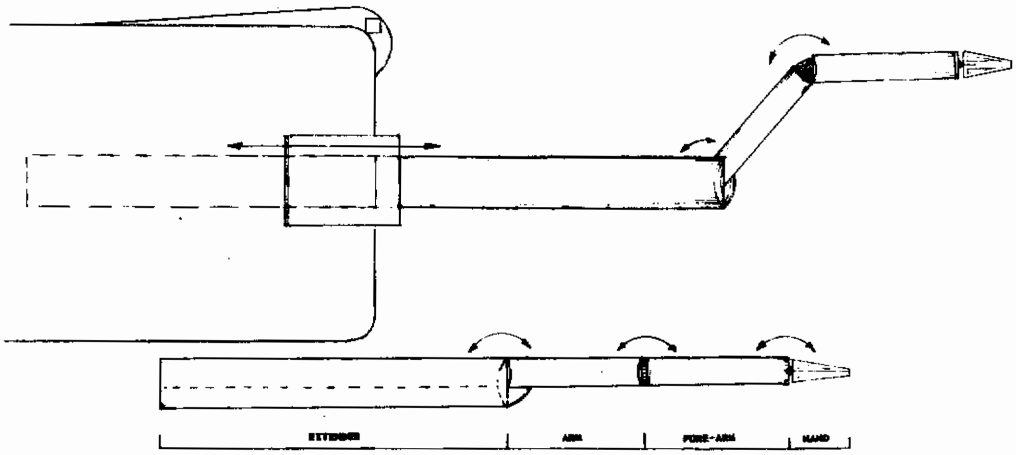

Figure 2. Concept of Retractable Manipulator Arm

Transfer of remote-handling equipment and methods to the space environment will also increase the complexity of visual access considerations (ref. 2). Problems related to the following conditions will have to be resolved: (a) empty field myopia, the continual fluctuation of accommodation in the absence of any detail capable of being brought into focus, resulting in impaired judgment of size, distance, and speed; (b) empty or unstructured visual field; (c) unidirectional illumination producing extreme contrasts and fluctuations between brightness and darkness; and (d) intense glare from objects reflecting sunlight in a relatively dark field.

Areas shaded from the sun will require good artificial lighting. Mirrors to reflect sunlight have been suggested. Intense glare may make viewing through shielding windows impossible at times. Therefore, provisions for indirect viewing through periscopes and television systems will be necessary. A refined stereotelevision system equipped with camera lenses capable of variable magnification could be used for both general and detailed viewing (see figure 1). Unmanned units operating at great distances from the control station could provide immediate visual feedback only through television systems. Undoubtedly the effectiveness of man's performance will gain much from research contributing to the resolution of visual difficulties.

Besides facilitating remote-handling procedure, sensory-feedback systems——visual, auditory, olfactory, and somesthetic——should contribute to the overall orientation and psychological well-being of the space man. Situations providing little or no sensory stimulation are very stressful to the human organism (ref. 2). Similarly, benefits derived from provisions which increase the level of confidence are likely to be especially important. The quantity and severity of risks should be reduced as much as possible——e.g., by using the space suit in addition to the tug life support equipment and by providing for securing or storing remote-handling accessories not in use.

The pressurized space cabin is analogous to the airtight hot cell. Hence, because of the sealing problem, electrical or electronic linkage is preferred over mechanical linkage for manipulators. Cabin space limitations will make gross movements of the master control of any manipulator-control system impossible. If the advantages of the master-slave concept are to be provided in space equipment, then master-slave congruity must be restricted to fine finger, hand, and forearm movements, and perhaps a limited amount of upper-arm movement. Part-time automatic auxiliary drives for gross positioning movements would make this feasible even with a mechanically linked manipulator. Increased ratio of slave movement to control movement is an alternative solution which warrants consideration.

Ease and effectiveness of human performance in space should be improved by additional research in:

a. Determination of efficient and economical means of remotely covering a large work area from confined quarters

b. Remote-handling performance as a function of different ratios of master and slave movements

c. Adequate identification coding of controls to permit simultaneous operation and observation of monitoring devices and external events

d. Feasibility of cooperative efforts involving two or more independent remote-handling systems

CONCLUSIONS

Many of the problems of remote-handling and space operations are interdependent. Solving one problem may reduce or preclude the need for consideration of other problems. Economical use of time and money is dependent upon good communication between equipment engineers and human factors scientists. Human factors people must be aware of the capabilities and intentions of engineers. Conversely, knowledge of man-machine difficulties stimulates engineering ingenuity. Conclusions derived from human engineering investigations, past and future, should be synthesized into principles and included in criteria for determining design characteristics of remote-handling systems.

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INTRODUCTION

To date, the concepts of manned space systems have restricted man primarily to a monitoring and scientific observer role, or, at best, the performance of a limited number of tasks that can be performed within the confines of his own space vehicle. It is pointless belaboring the obvious limitations of the present concept. However, the utility of man in space could be increased immeasurably by using remote-handling equipment.

TYPICAL SPACE TASKS

Some tasks that could be accomplished by remote handling are:

(a) Servicing operations

(b) Maintenance

(c) Destruction

(d) Inspection

(e) Assembly

(f) Rescue

(g) Exploration

DESIGN REQUIREMENTS

Even a very cursory examination of remote-handling requirements for space indicates a wide variety of factors that must be considered. One of the early steps is to define the degree of remoteness to be required, both environmental and psychological. The former would include such items as the physical characteristics of the object(s) to be handled (size, shape, weight, etc.), spatial separation, and automaticity of the handling equipment. The latter would include visual access (i.e., direct or indirect) and degree of translation of tactual and kinesthetic cues normally associated with motor activity.

Environmental Considerations

The effects of environmental phenomena such as temperature, illumination, relative acceleration, zero gravity, and radiation upon the task must also be considered.

Human Engineering

The design of the equipment and tools must minimize the energy requirements. Thus, time and mass are very important. As with any space venture, reliability must be high. In designing the equipment, the skills, the knowledge, and, consequently, the training of the operators must be carefully studied and analyzed. For example, problems of positioning, with six degrees of freedom, will undoubtedly require a far greater understanding of human coordination than is presently available.

Task Parameters

Some of the task parameters that should be considered are:

(a) Type and extent of inspections

(b) Maintenance and operational concepts to be used—i.e., remove and replace, troubleshoot, etc.

(c) Maintenance test and checkout procedures

(d) Control media to be used—i.e., hands, feet, elbows, knees, fingers, toes, etc.

Sensory Cues

Remote-handling equipment will eliminate all of the kinesthetic and tactual cues normally involved in manipulatory activities. While these kinds of cues will still be available, they will be second-order cues and may or may not be proportional to the original cues. The reorientation of other cues will place additional emphasis on the role of vision. Thus, the man will probably find it necessary to see both the manipulator and the object to be manipulated to accomplish the task with any reasonable degree of efficiency. This also suggests that direct visual access will not meet the visual requirements for other than the very gross handling requirements (e.g., it may be necessary to remove a component through an access door that normally could be done "blind").

There are a variety of ways in which the eyes can literally be extended through the use of optical systems such as periscopes or television. One might, for example, attach a small TV camera on the manipulator arm to provide continual visual access.

Maneuverability

The loss of flexibility inherent in remote-handling equipment and from the necessity of confining the man in an environment in which he can survive (whether in a suit or capsule) means that he will have to maneuver himself considerably to obtain the most advantageous working position. Almost nothing is known of man's capabilities to move efficiently in three-dimensional space, utilizing externally generated sources of thrust. More knowledge is also required concerning man's capability to integrated and utilize the kinds of information generated in a three-dimensional, remote-handling environment.

DESIGN APPROACH

A design approach to the orbital space worker problem has been given considerable attention by Bell Aerosystems Company. As previously indicated, there are many task- and operator-oriented variables that require further research before the roles of man and remote handling in space are defined and the problems resolved. The following approach is feasible and well adapted to the requirements of the space worker.

Figure 1 shows a configuration of REMORA, a small buoy-shaped capsule 6 feet high and 3 feet in diameter. It permits man to function in space while protected from the space environment. Its uses may include: inspection and maintenance outside of a space vehicle, material handling, assembly, transfer of personnel, and control module for space vehicles. The gross weight is approximately 500 pounds. The tinted glass dome provides access and 360-degree visibility. The astronaut may orient himself using the foot treadle which operates reaction jets. Work is accomplished using either the mechanical manipulators or the pressurized gauntlets. Grappling arms facilitate attachment to other vehicles. Internal environmental control is provided for 4-hour operation. A tether cable supplies electrical power and, if desired, retrieval.

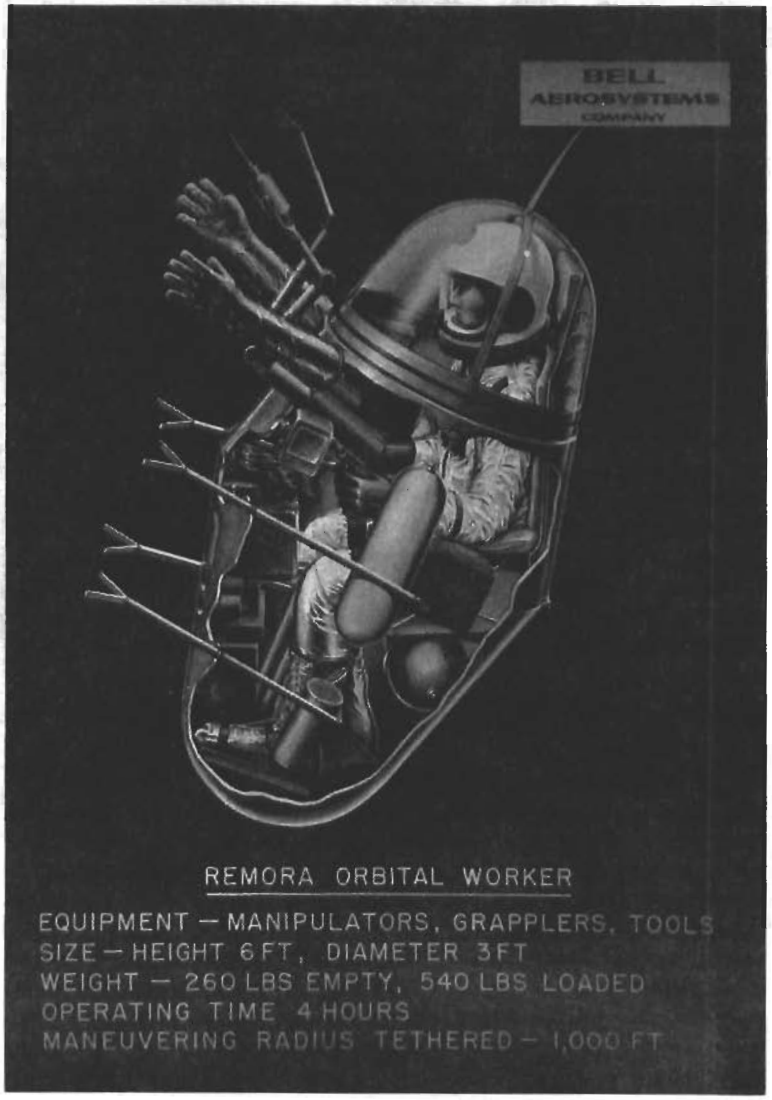

Figure 1. REMORA Orbital Worker

Extra-vehicular operation is illustrated in figure 2 showing both capsules and suited astronauts assembling parts of a space station, servicing, and photographing a satellite. Contact with the supply vehicle can be maintained by the tether cable. However, a short-duration untethered flight is possible.

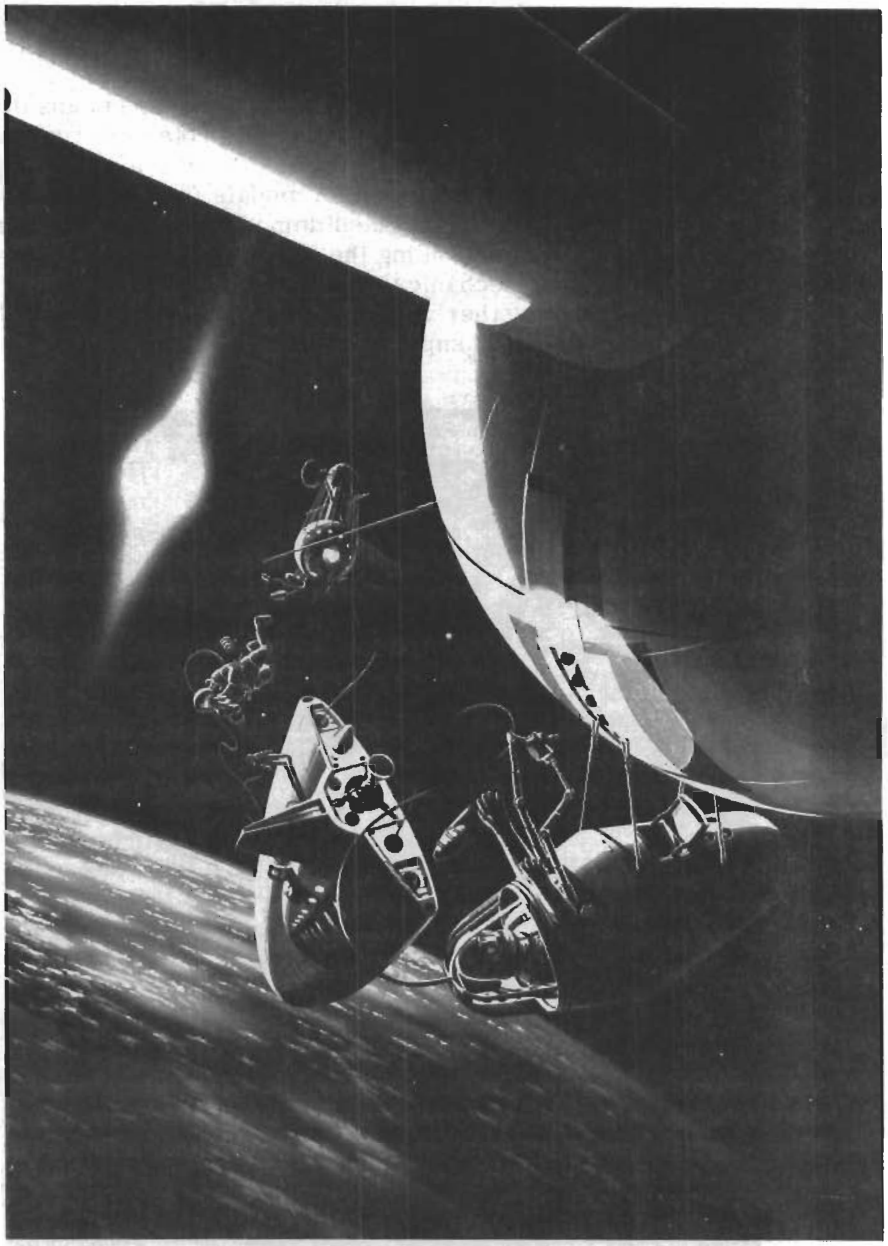

Figure 2. Extra-Vehicular Operation

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NONANTHROPOMORPHIC SPACE SUIT

The "Humpty-Dumpty," a nonanthropomorphic space suit (capsule), consists of an egg-shaped cylinder capable of supporting at least one man who is engaged in assembly, maintenance, or similar-type tasks in outer space (see figure 1). The capsule itself contains an ecological system capable of maintaining near ideal environmental conditions for approximately 30 hours. On the internal walls of the vehicle there are rotating panels which allow the astronaut complete monitoring of the environmental conditions of the vehicle and also afford him direct feedback as to the ongoing state of affairs of his propulsion system and many mechanical appendages. The astronaut sitting at his central control panel may, at his discretion, rotate the wall panels to a position which is most advantageous to him for the direction in which he is facing. The rotating panels are necessitated by the fact that the viewport of the vehicle completely circles the astronaut. Due to radiation hazards the viewport is covered by a rotating shield which may be positioned by the astronaut to face in any direction.

Fastened to this shield are two floodlights for operations conducted in the dark. Three of the specialized mechanical arms of this "astro-tug" may be rotated through 360 degrees around the tug and thus afford the occupant complete maneuverability without actually rotating the vehicle itself. These specialized arms have specially equipped hands composed of tools which may be utilized in outer space — e.g., drill, acetylene torch, paint and plastic applicator, screw driver, etc. Three fixed arms on the base of the vehicle are theoretically constructed to accomplish operations which call for powerful movements similar to those necessary for positioning two fuel tanks together, holding the astro-tug to a second vehicle while construction or maintenance is performed, and the like. Gripping is done through the use of finger-like clamps on the outer portion of the limb.

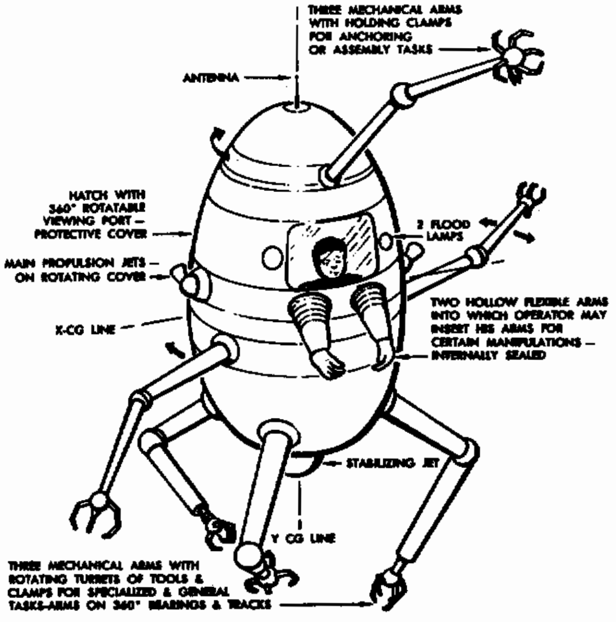

Figure 1. Humpty Dumpty Capsule

To effect propulsion and guidance of the system, three nozzles on rotating spheres are used. Two of these nozzles are located on the "x" center of gravity axis. These are responsible for the main propulsion of the unit. The third unit is at the bottom of the capsule and may be used to correct maneuvers conducive to tumbling or, if this vehicle is to be used in a gravity environment, this third unit may be used to suspend the capsule above the surface of the gravity environment.

While the astronaut is given complete manual control of the vehicle through the propulsion system, he may also utilize the inertial platform of the capsule to maintain any position automatically and thus free all six mechanical arms for a complex task. Control of all six mechanical arms is accomplished through the central control panel via fingertip control. The arms act in response to any movement of the hand.

Two internally sealed, anthropomorphic-type arms have been included on the vehicle so that, in case there is some specialized or precise type of task to be done which is not a direct capability of the mechanical arms, the operator may insert his own arms into these flexible shieldings and perform the operation.

Access to this vehicle is attained either through a hatch constructed in the plexiglas front or through a doubly sealed hatch on the top of the capsule.

PROJECT MERCURY CONVERTED CAPSULE

A second concept for a nonanthropomorphic-type space suit would essentially be constructed from off-the-shelf items. It would be possible to utilize the Project Mercury Space Capsule and re-entry body as a space suit for assembly, maintenance, or similar-type functions. To do this, the major additions to the system would merely be a translucent plastic observation port on the forward portion of the capsule and an assembly of mechanical arms to be attached in place of the parachute package. These arms could in turn be foldable into their shaft holder. Figure 2 illustrates this design configuration. Modifications of the capsule would also be necessary in that the fuel tanks for propulsion would have to be enlarged to allow maneuvers in space. The interior would have to be slightly rearranged to allow inclusion of controls and panels associated with the mechanical appendages. While there are many disadvantages to this system (e.g., provisions for stabilization of attachments to a second vehicle while accomplishing tasks are presently not considered feasible), the most immediate advantages are the decreased cost of development and the fact that this vehicle may be included in a satellite system for utilization as an escape vehicle which is readily altered, while spaceborne, into an astro-tug.

The feasibility of a capsule of this nature must be considered in any future analysis of an extra-vehicular space suit.

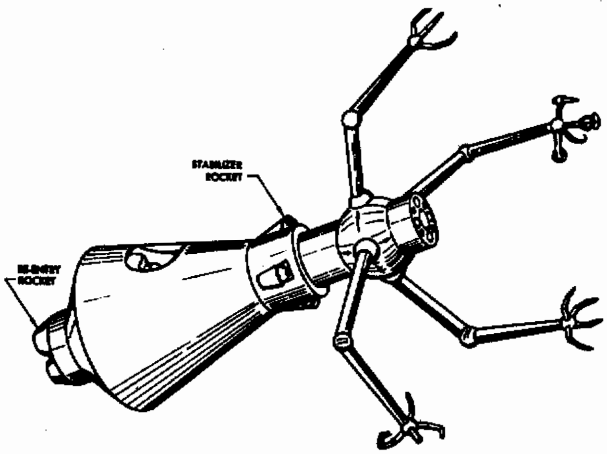

Figure 2. Project Mercury Converted Capsule

CONCLUSIONS

The above designs, i.e., the Project Mercury converted capsule and the "Humpty Dumpty" unit, can be considered as first-generation, feasible, nonanthropomorphic devices. A much more speculative concept, but in every sense within our technological reach, is shown in figure 3. This is basically a space tug and repair vehicle and is spheroidally shaped. Viewing this figure, we see:

a. The control console will release doors on mechanical arms and legs, select various extensions, select self-viewing TV cameras, select receivers (communications), and regulate gyro control.

b. The 3-D helmet is a contained electronic unit and inside is a dot-type screen instead of the usual cathode-ray tube. The image surface is hemispheroidal to reproduce real optical effects. The hemispheres would fit on the face over each eye to achieve stereoscopic effects. As the observer rotates his head he picks up the next camera transmission—not as a separate picture but as a continuously integrated picture. In actual use, the helmet could be reduced to a much smaller head set.

c. Expanding arms use servomotors with variable current control. They are run by operational gloves.

d. When the operator is positioned in the attitude seat, he has as complete attitude control of the sphere as he has of his own body.

e. Television cameras are placed on the main periphery of the globe.

f. Jet stabilizers are located between the cameras.

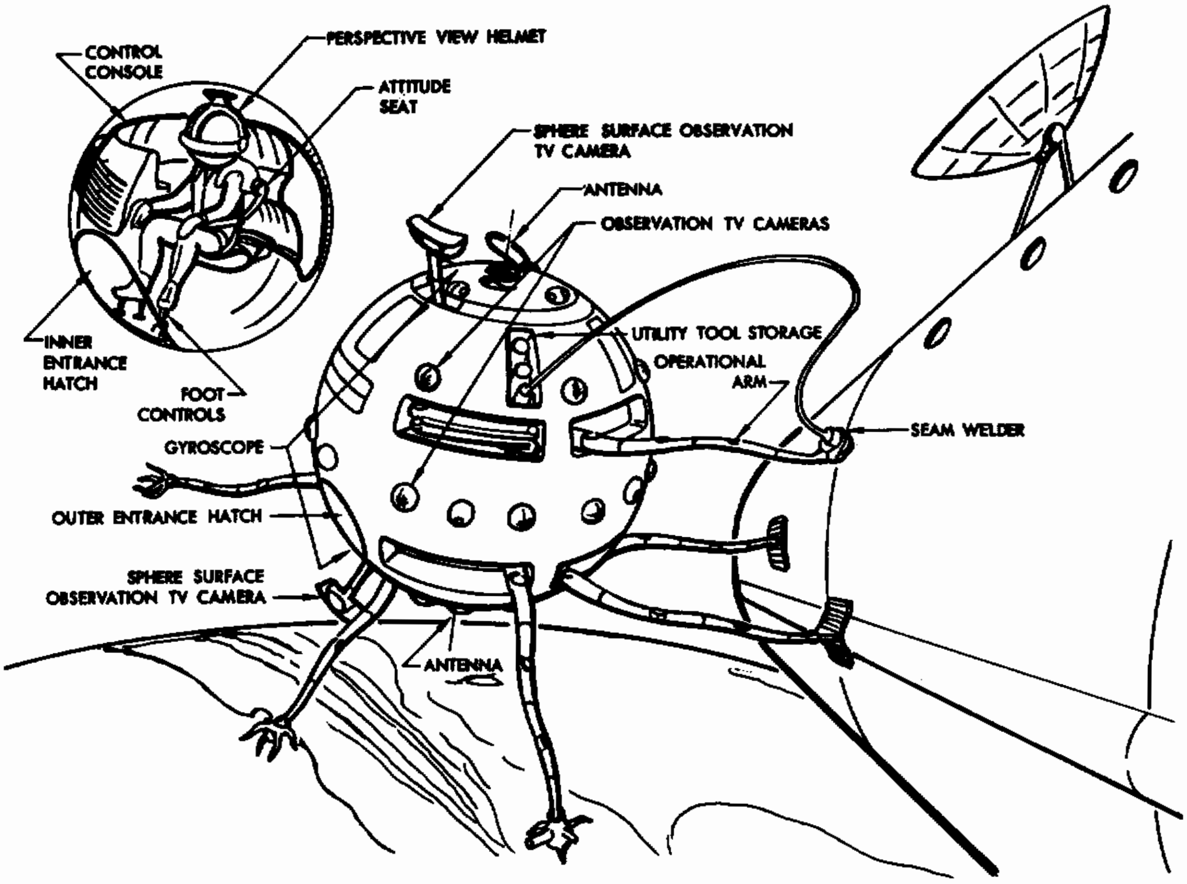

Figure 3. Proposed Nonanthropomorphic Space Suit

MISSILE AND SPACE VEHICLE DEPARTMENT
GENERAL ELECTRIC COMPANY
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INTRODUCTION

The General Electric Company has been active in the manipulator and remote-handling equipment fields for several years, primarily in connection with its nuclear laboratories and test facilities. The application of remote-handling equipment to operations in space and lunar situations is a logical extension of the work in remote handling. Remote handling will play a definite role in the exploration of space. Investigations of remote-handling equipment for space operations have indicated that considerable research and development work will be required to produce functional remote-handling systems capable of performing the necessary tasks in space.

A great deal of material has been written about the hazardous nature of the space environment, which precludes the necessity of discussing the reason for remote handling in space. Remote-handling equipment should and will be used wherever possible to eliminate the necessity for directly exposing man to space. Normally, the first approach to design for remote handling for earthbound situations is to avoid it whenever possible. The opposite approach, to make maximum use of remote-handling design principles in designing space vehicles and equipment, may well be required. The remote-handling equipment will require new design approaches of a revolutionary rather than evolutionary nature.

TYPICAL SPACE TASKS

Many tasks in space may have to be performed by remote-handling equipment. In the near-earth orbital region, which ranges roughly from 400 to 600 miles above the earth, there are many proposed programs for satellites, manned vehicles, and space stations which will require utilization of manipulators and remote-handling equipment. Such tasks as assembling and disassembling, loading and unloading, inspecting, testing, handling, checkout, and servicing can be performed by remote means. Remote equipment will undoubtedly play an important part in the maintenance of satellites and space stations (see figure 1). Manipulators might be used as a device for grappling, docking, and mating between vehicles or subassembly sections. Several conceptual vehicles for orbital operations, such as the popular space tug, have included manipulators as an integral part of their design.

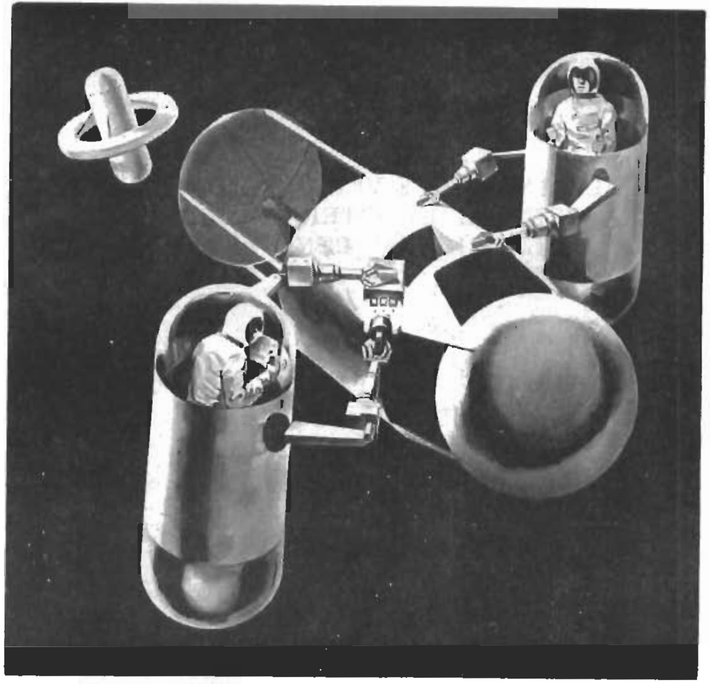

Figure 1. Manned Space Capsules Outfitted with Remote Manipulators Performing a Typical Space Task

LUNAR MISSIONS

The broad area of lunar missions will include many applications for remote-handling equipment. In addition to the tasks already mentioned, exploration, sampling, and experimentation might be performed remotely. The construction and servicing of lunar base facilities, particularly nuclear power systems, may well be handled by remote equipment. A simple, compact, highly dextrous manipulator may be required as an integral part of a space suit to overcome the problem of the gloved hand and to provide a space-suited man with some semblance of manual dexterity. Wheeled or tracked vehicles capable of lunar surface mobility will use remote-handling equipment to perform a variety of functions (see figure 2). As the conquest of space moves from exploration through economic development to mature economic operation, the projected advances in the state-of-the-art of remote-handling equipment dictate that such equipment will be used to an ever-increasing extent in space.

PROBLEM AREAS

There are, of course, many problem areas associated with the design and development of remote-handling systems for space applications. A rather detailed analysis of the remote-handling tasks for each specific mission will be required. The problems of force feedback and tactile perception are important in terms of the information furnished to the operator of remote-handling equipment and manipulators, as well as the "body image" and "frame of reference" problems. The competent operation of remote-handling equipment is heavily dependent upon visual access. Should this access be remote or direct, using optical or television techniques? The areas of output control, control transducers, and control actuation require considerable study. Present control actuation methods for manipulators do not appear to be operable in the space environment. Pneumatic or hot gas actuation systems seem to hold promise for application to manipulators. Similarly, the results of concurrent work in the fields of materials, structures, mechanisms, bearings, and seals for space vehicles and equipment will have to be implemented. Special effort may be required in these areas to solve problems peculiar to remote-handling equipment. Early recognition and definition of all of these problem areas are instrumental to development work for space remote-handling systems. Basic research will undoubtedly be required in many of these areas.

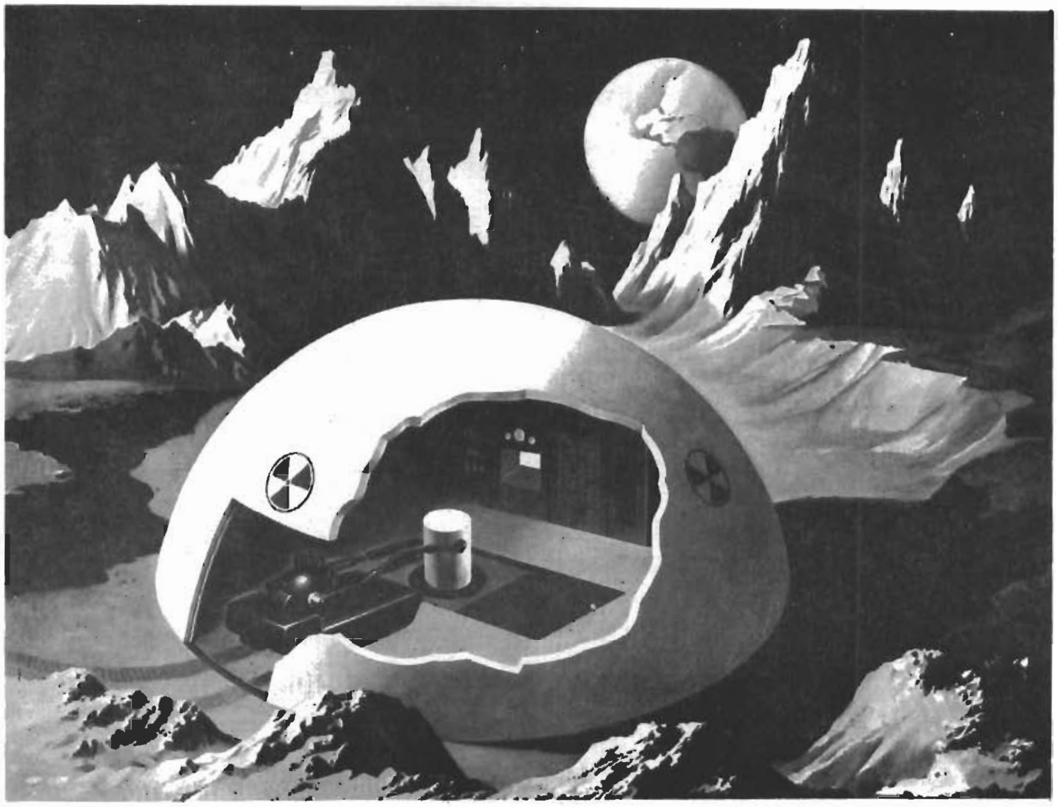

Figure 2. Tracked Lunar Vehicle Working in a Lunar Nuclear Power Plant

GENERAL DESIGN

Many general design characteristics of manipulators and associated equipment are already apparent. Early space manipulators are expected to be simple and rugged, with somewhat limited dexterity and force reflection capability. They will be capable of simple, basic movements and operations. The relative simplicity of these early models will necessarily be due to problems with such items as materials, bearings, seals, and control actuation. Also, the size and weight of equipment associated with manipulators, particularly electrically controlled manipulators, limit the complexity and dexterity of these early systems since there is a limit to early booster payload capability. Early remote manipulators will probably be used to position, locate, and place in operation special, self-contained automatic mechanisms or programmed machines capable of specific operations as required by the specific mission in order to provide the overall remote-handling system capability. A new approach to the design of this equipment is required using previous designs and configurations as guide lines rather than as first approximations. The established philosophy of designing vehicles and equipment to be handled or operated on by remote means so as to augment the remote-handling equipment itself will have to be used to a very great extent. This includes consideration of such things as grasping points, register points, orientation indicators, and pilot pins.

CONCLUSIONS

As advances are made in the many technologies used in remote handling, equipment will become more complex and capable of a greater variety of operations. The role which remote handling plays in space can be a large and vital one. Just how large depends upon how much timely development work can be started to make equipment available when the need for it arises. Careful planning and study, along with the early initiation of development programs, will insure the future of remote-handling equipment in space.

Donald F. Melton

MECHANICAL DIVISION
GENERAL MILLS, INC.
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INTRODUCTION

Remote-handling systems can be defined as combinations of equipment the primary purpose of which is to move items relative to each other in a controlled manner. The system includes not only the actuators and structures required for the physical tasks to be performed, but also the viewing, sensing, control, and power necessary for operation. In a broad sense, this definition includes the overall vehicle system. There undoubtedly will be complete space vehicles devoted entirely to remote-handling missions. In a more limited sense, the remote-handling system will be a subsystem integrated into the overall system in terms of power supply, communication and control links, and compatible configuration.

The items to be handled may be separable remotely from the handling equipment—as, for example, a powered tool— or may be permanently attached to it— for example, an integrated television camera.

Remote can be considered to be any location beyond the human operator's reach. Remote-handling systems are required where the operational environment is not suitable for occupancy or when the objects to be handled and the distances they are to be moved are beyond the force and reach capabilities of a man.

The environmental conditions in space, as well as on the moon and most, if not all, of the planets, are such as to make direct human contact impossible. Remote-handling equipment will be required.

The potential applications for remote-handling equipment in space are many, and can be said to include any of the manipulative tasks done directly by a person under normal conditions.

ARM-HAND WORK TASKS

A listing of specific space tasks would be long and would be incomplete within a short time, as new missions are determined. Instead of this detail listing, the work tasks normally done by a person's arm and hand, which will probably be performed by remote-handling systems in space (see figures 1, 2, and 3), can be categorized basically into:

a. Grasping and holding— e.g., grasping and holding one space vehicle from another (figure 1)

b. Transferring —e.g., transferring a power supply from a support vehicle to an operational vehicle (figure 2)

c. Orienting—e.g., orienting a television camera to view an approaching object (figure 3)

d. Guiding—e.g., guiding a cutting device to gain entry into another object (figure 2)

e. Applying of forces and torques—e.g., applying a force to insert or pull shear pins, or a torque to tighten or loosen bolts in the orbital assembly of a space station (figure 1)

f. Sensing of forces, temperature, roughness, hardness, etc.—e.g., sensing the hardness of a foreign object by means of a manipulator-held sensing device (figure 1)

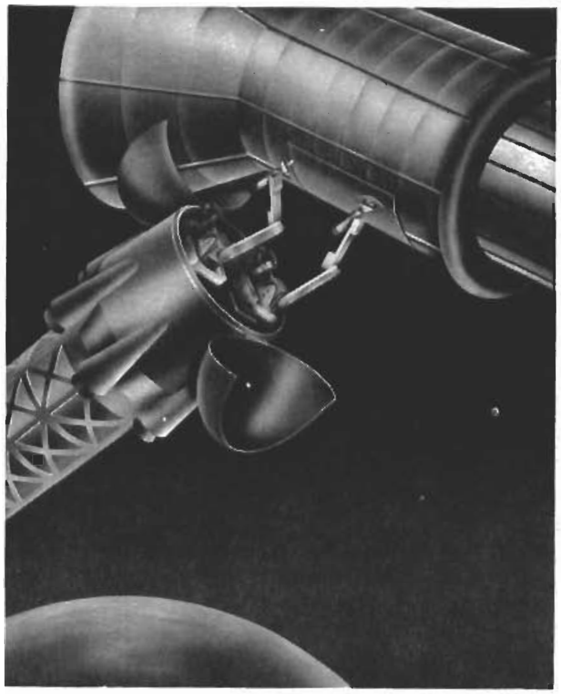

Figure 1. A Pair of General Mills, Inc., Model 150 Manipulators Adapted for Space Use

Illustrates typical grasping and holding, applying of forces and torques, and sensing of hardness, temperature, etc.

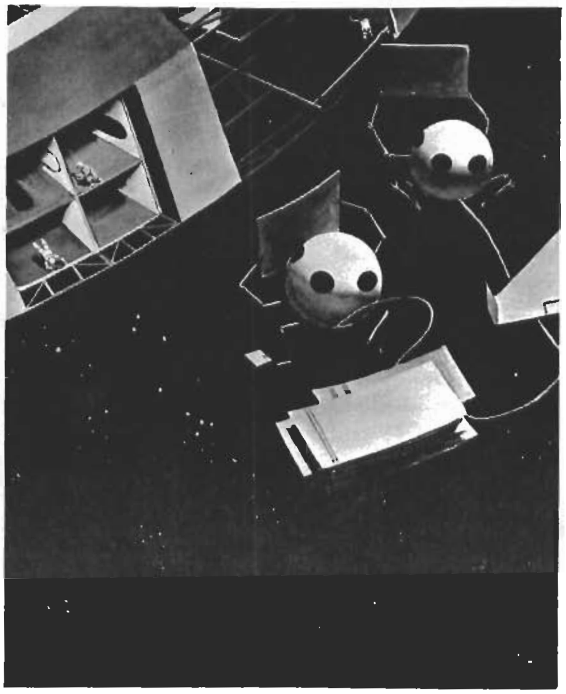

Figure 2. Typical Space Manipulator Applications of Transferring and Guiding

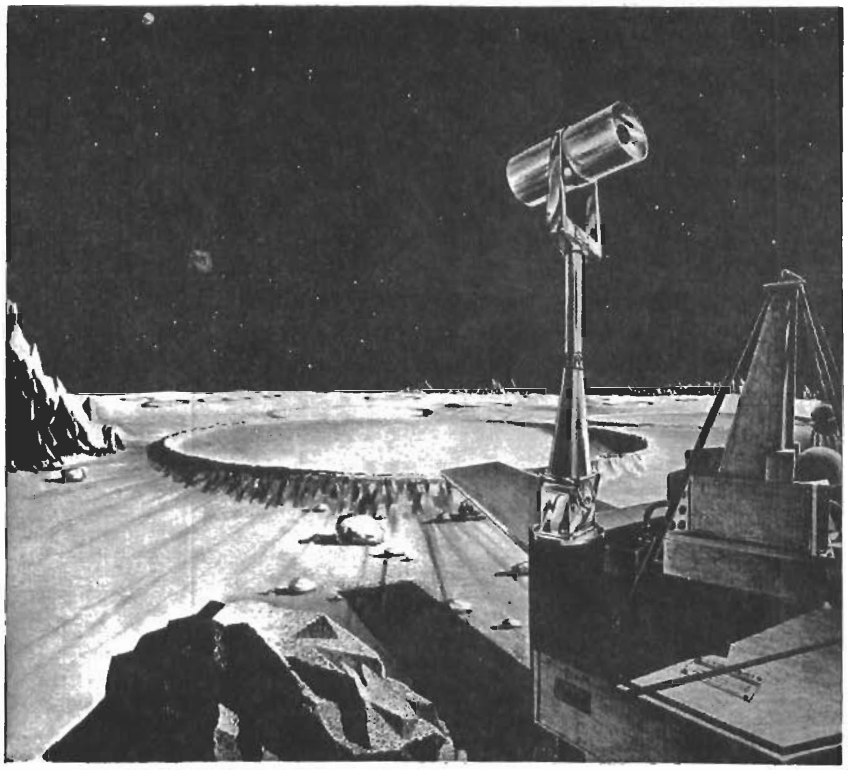

Figure 3. Manipulator with an Integral Television Camera, Typical Orienting Application

ENVIRONMENTAL CONDITIONS

The design considerations important to remote-handling equipment for use in space include careful analyses of and provision for the environmental conditions to be met in space as well as during prelaunch and launch conditions.

Temperature

The temperature at which the equipment will operate in space is determined by the radiation balance of the equipment, the vehicle on which it is mounted, the sun, and any other mass close enough and with sufficient temperature difference to be significant, as well as any heat generated within the equipment. "Hot" and "cold" radiation zones in the spherical angle surrounding the equipment can be used to advantage. Selective coating of the external surfaces can be used to control the internal temperature. Lunar- or planet-based operation imposes a more severe problem than in space because of the strong ground effect.

A directed or collimated thermal antenna can be of value in selecting desirable radiation zones. Thermal insulation is advantageous in reducing fluctuations in temperature as the radiation field changes.

With existing high- and low-temperature components and materials, and with proper design for temperature regulation, satisfactory operation can be obtained. In special cases, materials can be selected to operate satisfactorily without special temperature-control devices.

Pressure

The high-vacuum operation encountered poses a considerable design problem in providing suitable bearings and mechanisms and the lubrication for them. Three approaches to this problem are: (a) to seal the housings in which the bearings and mechanisms are contained to enable conventional lubricants to be used, (b) to use low vapor-pressure lubricants which will operate in the vacuum for the required time, and (c) to use bearings and mechanisms that require no lubricants.

High-Energy Radiation

The radiation levels as established to date do not pose serious problems.

Micrometeorite Collision

The impact and erosion levels do not appear serious. The change in emissivity of surfaces used for temperature control, due to erosion, can be anticipated and provided for.

GENERAL DESIGN PRINCIPLES

Reliability

The reliability requirement is of prime importance and is best obtained by basic simplicity. Complex designs must be avoided.

Weight and Efficiency

Because of the high cost per pound of placing a system in space, the weight must be a minimum commensurate with the high reliability required. The power required to operate the remote-handling equipment, and therefore chargeable to it, can be expressed in terms of weight, either as pounds per watt-hour in the case of energy-storing or fuel-consuming devices, or as pounds per watt-hour for regenerative supplies such as solar cells. High efficiency throughout is required to minimize the power-weight requirement.

Safety Features

Remote-handling equipment should incorporate provisions for accommodating reasonable operator error without damage to either the equipment itself or to the objects being handled. The equipment should be able to withstand any force which the operator can impose by the controls. Typical of these features are clutches and circuit protectors to prevent inadvertent overload, and limit switches to confine the displacement of the manipulator elements within specified limits. Careful selection of maximum speeds will prevent the operator from making accidental excessive motions.

Human Engineering

In brief, the equipment must be designed so that operation is as simple and comfortable as possible. This, as are other system considerations, is a field in itself.

Control

Highly repetitive operations, or very simple ones, may justify the additional complexity of programmed control. Upon receipt of an initiating signal, the equipment would perform its function without further operator attention. Simple functions such as automatic folding and stowage of the equipment can be programmed.

There are two basic types of operator control: (a) rate control, where the displacement of the control handle establishes the direction and rate of motion of the controlled element, and (b) position control, where the displacement of the control handle causes a corresponding displacement of the controlled element. Force reflection or indication can be incorporated into both types of control.

Both of the control types have advantages. The rate control is inherently simpler and more stable. The system can easily incorporate a self-locking feature so that all elements will hold their positions, without a power drain, until a control signal is supplied. Inadvertent motion by the operator does not cause a violent motion of the equipment. The operator can take his hands off the control handles at will, and can concentrate on one motion at a time. Proper consideration of the human engineering aspects of the controls can make the operation quite natural. The operator is required to integrate the rate of motion with time to reach a given position.

The position control in most cases provides for faster operation. The controlled element follows the operator's movements directly. As noted above, this type of control is more complicated and more demanding on the operator to keep his hands continually held steady in the required location.

At least for first applications, it appears that the rate type of control is best.

It is desirable to minimize the amount of control equipment located on the remote vehicle. Equipment located on the ground can easily be maintained and replaced as required.

The distance between the operator and the remote-controlled equipment is important in terms of the signal transmission time. At a distance of 250,000 miles, for example, transmission of the signal from the operator's station to the remote equipment takes about 1.3 seconds, and the returned television or other position indication, an equal time. Thus, there is a 2.6-second delay in the operator's knowledge of the result of his control action. Delicate operations should be performed slowly to allow for this lag.

CONCLUSIONS

Because of the environmental conditions in space, remote-handling equipment will be required for both manned and unmanned systems. With careful design—including thorough analysis of weight, power, strength, and efficiency with special attention given to the material selection—and consideration of the operator's role, remote-handling systems for space use can be built with present technology.

John W. Clark, Ph.D.

NUCLEAR ELECTRONICS LABORATORY
HUGHES AIRCRAFT COMPANY
CULVER CITY, CALIFORNIA

ROLE OF REMOTE HANDLING IN SPACE

Orbiting Vehicles

In connection with orbiting vehicles, remote-handling techniques can advantageously be employed in connection with maintenance and repair, assembly in orbit, and personnel transfer.

Maintenance and repair is, of course, confined to orbiting vehicles so expensive as to justify the cost of orbiting a repair system rather than orbiting a complete new satellite.

Assembly of large orbiting vehicles may advantageously be accomplished by remote-control techniques. These techniques will permit the assembly of vehicles far too large to orbit in a single payload. Control of the assembly system may be accomplished either from a ground station or from a manned orbiting vehicle.

Personnel transfer, as, for example, between a re-entry vehicle and a manned space station, may be facilitated by the use of remote-control techniques in accomplishing the final contact between the two space vehicles and in accomplishing an airtight closure or junction between these two which will be safe for personnel transfer.

Lunar Applications

Remote-control techniques will find many applications in the exploration and development of the lunar surface for scientific and military purposes. Preliminary operations will probably be accomplished by systems controlled from the earth. This may be followed by development of lunar sites, also by earth-controlled vehicles.

After the development of lunar sites, manned lunar expeditions may become feasible. Such expeditions will benefit from the availability of sophisticated remote-handling vehicles which can, under control of the pilot of the space ship, accomplish lunar exploration or advance the development of the sites prepared by the earth-controlled Mobots.

Finally, after habitable lunar stations become available, operations of all kinds upon the lunar surface will still be in large part carried out by Mobots under control of the inhabitants of the lunar station.

DESIGN OF REMOTE-HANDLING SYSTEMS FOR SPACE

This discussion excludes consideration of lunar Mobots. It is, of necessity, confined to certain of the problems uniquely applicable to remote handling in connection with orbiting space vehicles.

Vision

The most important of the senses, vision, requires particular consideration under space conditions. The harsh illumination will require unusual control of the TV cameras, and also may require specially controlled illumination as an aid to working on the shadowed side of orbiting objects. The lack of background and of vertical reference are serious psychological problems. Consideration may well be given to artificially inserting both background and vertical reference within the TV system so that the operator's TV monitors present him information similar to that to which he is accustomed.

These requirements are superimposed upon those applicable to any remote-handling system. Sufficient experience has now been gained with operation of Hughes Mobots to make one confident that adequate vision for performing complex or precise tasks can be furnished to a trained operator by the appropriate use of two or more conventional TV cameras. Additional quantitative studies concerning the relative utility of multi-camera, stereo, and other methods of vision, with specific reference to the conditions existing in space, will be most valuable.

Dynamics of a Gravity-Free Environment

Operations under orbiting conditions present a novel situation since one is concerned with accelerations rather than velocities and a relatively small system of limited power consumption can direct the motions of quite heavy objects if appropriate consideration is given to their inertia. For example, an arm capable of lifting an earth weight of 40 pounds can impart a useful acceleration to much heavier masses under weightless conditions. This arm can move a 500-pound mass 5 feet in 2.8 seconds in an optimal situation in which a mass is accelerated for one-half the time and decelerated for one-half the time. Clearly, special operator training will be required to obtain successful performance under these conditions, so different from those to which we are accustomed.

Command and Data Link

In cases in which control is provided from a manned space craft, the command and data link can be transmitted from controlling vessel to Mobot via cable. The time division multiplex command system utilizing trinary digital coding is particularly suitable since it requires only two conductors in the cable. This system has been described in detail in an article by Don A. Campbell (ref. 1). Situations in which radio command is required are also well handled by this same system, which minimizes bandwidth required of the communication channel. The data link which conveys vision, sensory, and other analog information from Mobot to command station can employ the same cable as does the command link. In radio-controlled systems a separate data link is required. The detailed considerations, primarily the trade-offs between power and bandwidth, are different in each case. Particular attention must be paid to utilizing TV systems in which minimum video bandwidth is required in comparison with the conventional RTCA* standard system which is quite wasteful of bandwidth.

Arm Geometry

Numerous space applications are best handled by specific mechanisms tailored to perform specific tasks. No general comments can be made about such mechanisms. There is, however, a definite need for general-purpose handling mechanisms. To meet this need, the Hughes Mark 2 Arm has been developed (figure 1). Its three articulations are each capable of ±90° motion in either plane. The tong rotates continuously. Its parallel jaws open to a 4-inch width or close completely. They will rotate continuously in either direction. This arm is completely self-contained. All actuators and other mechanisms are included within the arm structure. The only auxiliary space required is that occupied by the command system. This arm is not presented as the ultimate arm design, but is presented as indicative of a general-purpose arm capable of handling a wide variety of manipulative requirements in the presence of obstacles or in cramped quarters.

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* Radio Technical Committee for Aeronautics

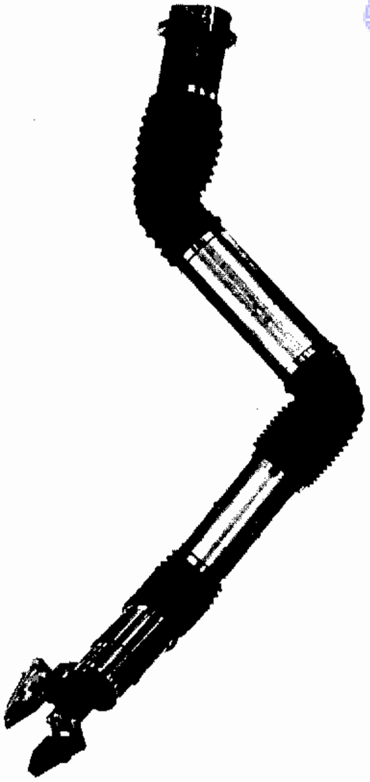

Figure 1. Hughes Mark II Remote-Control Arm

This is a typical, general-purpose manipulating arm now under evaluation by Hughes Aircraft Company

Locomotion

In connection with satellite and orbital vehicle handling arms, only two methods of locomotion appear feasible. These are rockets or jets for traversing the space between one orbiting object and another, and auxiliary arms for moving about on or in a large orbiting vehicle. The preliminary sketches of space Mobots (figures 2 and 3) indicate a four-armed Mobot based on this concept. In general, two of its arms are employed for moving it about in connection with its operations on an orbiting vehicle, while the other two are free for performing any manipulations required.

The Space Environment

The space environment (high vacuum, extremes of temperature, zero gravity, etc.) will have a controlling influence on the detailed design of the components which make up any space Mobot. Fortunately, adequate design information is becoming available upon which one can base such engineering design. Further environmental test facilities are becoming available in which components or complete systems can be tested to insure their performance in the space environment.

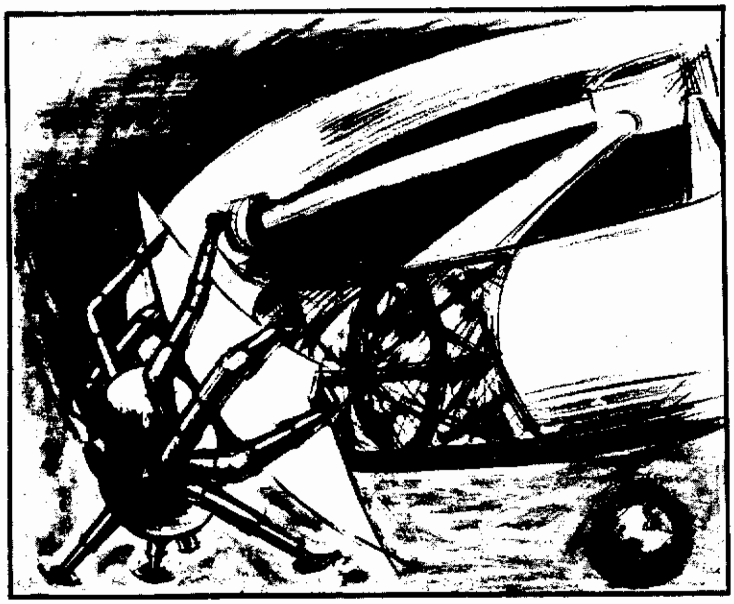

Figure 2. Artist's Concept of a General-Purpose Space Mobot Completing the Assembly of a Large Orbiting Vehicle

In this concept the Mobot's motions are controlled from a ground station. The command and data link may be relayed via communication satellites to maintain communication with the Mobot in all orbital positions.

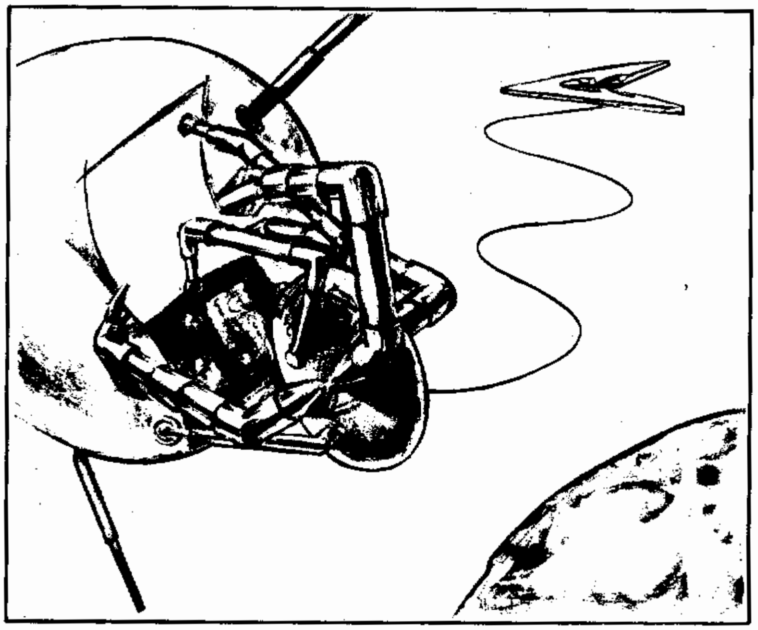

Figure 3. Artist's Concept of a General-Purpose Space Mobot Performing a Maintenance Function on a Complex Satellite

Note the use of general-purpose, multi-articulated arms and cable control from a manned space vehicle.

SUMMARY

Concepts

The above discussion of the role of remote handling in space leads to the preliminary concepts shown in figures 2 and 3. These Mobots employ jets or rockets to move about in space. They are furnished with four arms and two "eyes." The four arms, which are identical, can be utilized for moving the Mobot about on the vehicle on which it is working, positioning it during performance of the task, or guiding or manipulating the objects handled. Even a relatively small Mobot, such as those in figures 2 and 3, can handle quite heavy objects in space if the operator is properly trained in the dynamics of space operations as outlined in the above discussion of the gravity-free environment.

These Mobots may be controlled by cable from a manned space ship or from a ground station by radio beams. In the latter case, it may be necessary to utilize orbiting vehicles as relay points for control of Mobots which do not stay within the visual horizon of any one ground station.

CONCLUSIONS

The work performed to date at Hughes on the electronically commanded, remote-control systems to perform complex operations has demonstrated the feasibility of this method of accomplishing useful work in a hazardous environment. Work now in progress demonstrates the feasibility of designing mechanical and electronic structures which will perform in a satisfactory manner in the environmental conditions which prevail in space. Space Mobots are technically feasible and can be engineered economically and effectively to accomplish any given tasks which may be placed upon them by our space program.

REFERENCE

1. Campbell, D.A., "Multiplex Circuits for Control of a Robot," Electronics, 22 January 1960.

LOCKHEED AIRCRAFT CORPORATION
LOCKHEED-GEORGIA COMPANY
MARIETTA, GEORGIA

INTRODUCTION

The first manipulative tasks required of man in a space operation will be those associated with establishing a station in orbit or with operating a manned vehicle or station in orbit. Practical environmental control systems required for human survival will probably result in performance degradation at best and total incapability at worst.

It is assumed that a human operator will be necessary to monitor, control, or perform assembly and repair operations in space. The various degrees of human input in increasing order of human contribution are thus typified in:

a. Self-repairing or self-assembling systems

b. Robot-repairing or robot-assembling systems

c. Human operator-repairing or human operator-assembling systems

The self-repairing or self-assembling systems are systems which are completely mechanized. Since the space environment will not affect their basic functioning substantially, only monitoring is necessary.

The robot-repairing and robot-assembling systems add mobility to the required operations. However, such systems have seldom proved satisfactory in the earth environment and their deficiencies are compounded in space.

The most useful and the most promising vehicle systems are those which utilize, in the most direct manner, human capabilities. The equipment which maintains a habitable environment for the human operator while accomplishing his task and the equipment which provides the means of performing the tasks are considered to constitute a vehicle system.

A detailed theoretical study on construction of specific space systems for remote handling does not seem to be warranted until simulation is available to confirm the analysis. Thus, development of a simulator with this capability is essential. Recognizing this, the Georgia Division of Lockheed has established some broad requirements for space systems and is using them to study and establish simulator requirements and concepts.

THE VEHICLE SYSTEM CONCEPT

A general description of one type of vehicle system that might be used for remote handling in space is presented to illustrate how simulation of such a system might be accomplished. A typical sequence of tasks to be accomplished in space station assembly might be:

a. Secure components to prevent drift.

b. Locate specific component package.

c. Restrain component and move to assembly area.

d. Remove protective covering and prepare for assembly.

e. Index components to be assembled.

f. Hold indexed components during attaching act—such as bolting, riveting, or welding.

g. Seal and make wiring and plumbing connections.

Once the primary need and mission of such a vehicle system is established, secondary applications should be studied. Such applications for a space station assembly and maintenance vehicle system might be:

a. Recovery of payloads boosted to the vicinity of a space station

b. Transfer of personnel or cargo between space stations

c. Emergency escape

d. Satellite inspection

Studies and reports made by Lockheed-Georgia Division indicate that the best vehicle systems will probably result from a philosophy which minimizes vehicle mass. Due to the environment and basic physical relations, it seems unlikely that any "Sunday Funny" type space suit will be practical. Thrust nozzles will be fixed to a rigid frame and have some degree of automatic control. Such a system requires fuel for accelerating and then decelerating. If the vehicle mass becomes excessive, the amount of fuel required becomes large and aggravates the situation. By assuring that research and test equipment is designed into the space stations rather than into these utility vehicle systems, a lightweight vehicle system should evolve. Examples of such systems are shown in figures 1, 2, and 3. These concepts are described in refs. 1 and 2.

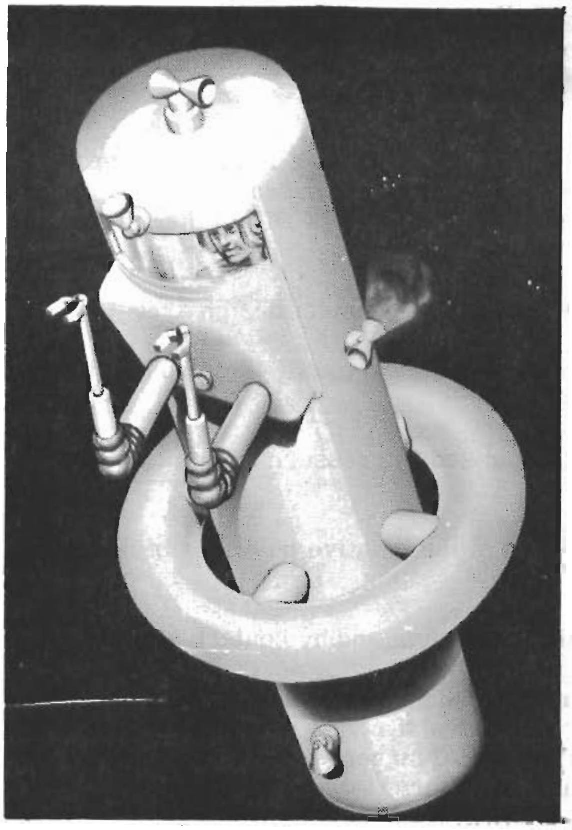

Figure 1. Cylindrical Vehicle Concept

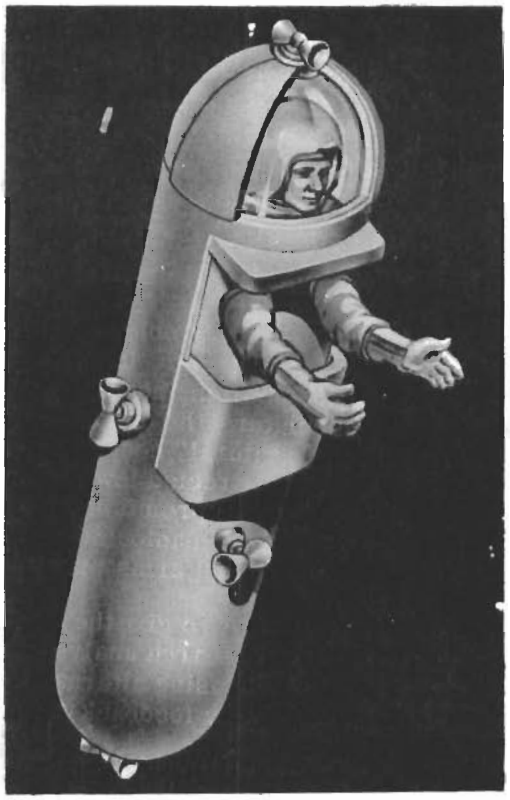

Figure 2. Cylindrical Vehicle Concept with Fabric Armpieces

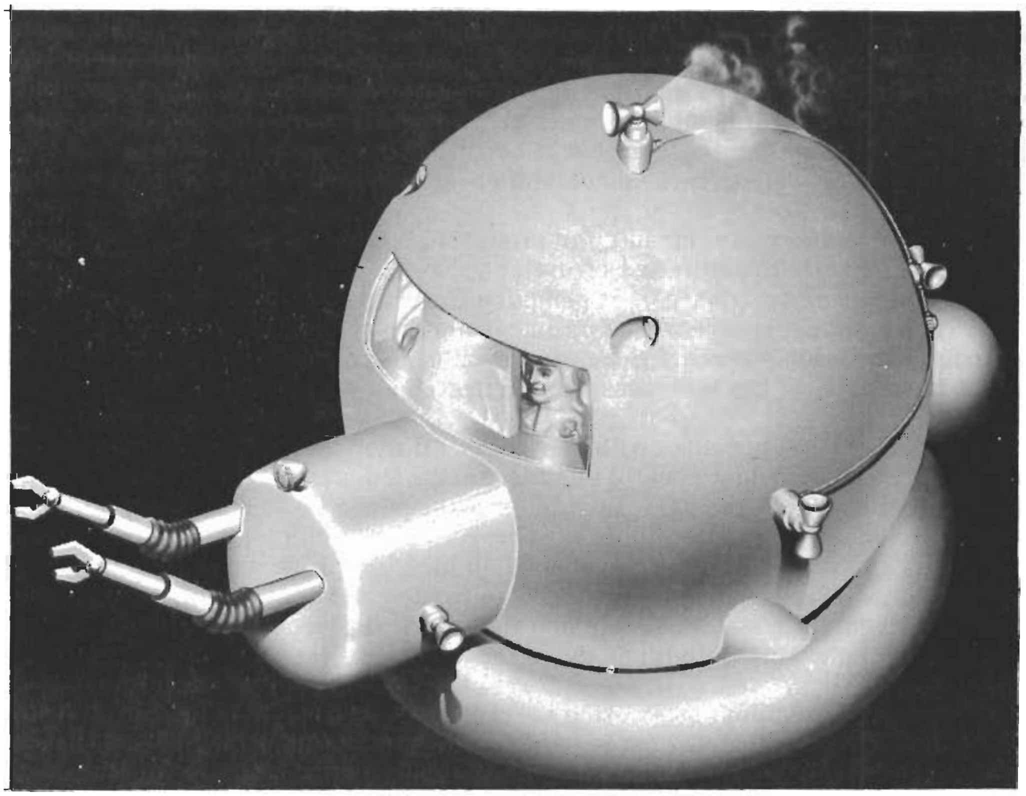

Figure 3. Spherical Vehicle Concept

THE USE OF SIMULATORS

The efficient utilization of man's capabilities in space flight systems requires a capability to: (a) define his specific task contribution to the mission, (b) select the overall environment to which he is to be subjected, (c) evaluate his performance of the specific tasks within the environment provided, and (d) train him in order to improve his performance.

The principal environmental conditions of interest in vehicle system design are:

(a) Accelerations in six degrees of freedom resulting primarily from control impulses and contact with other bodies

(b) The gaseous environment which is compromised in pressure and composition but optimum in temperature

(c) The external visual environment composed of the relative positions of heavenly bodies and other manmade vehicles

(d) The aural environment generated within the vehicle and by contact with other bodies

As a result of the divergence of the flight system environment from man's natural environment and the complexity of space flight systems, the evaluation of man's performance and his training must receive considerable attention in the future. It thus seems imperative that space flight simulators be developed which will permit testing and evaluation of space equipment and training of vehicle system operators.

Man's experiences in space flight will be represented by the sum of the environmental factors which he perceives. The objective of space flight simulation is the representation of the total anticipated environment with sufficient realism to induce the same physiological and psychological responses that will occur in the true situation being represented.

Considering the diversity of situations to be simulated, it does not appear feasible or expedient to provide a single simulator to meet all phases of space flight from launch to re-entry and landing. For simulating the most probable conditions associated with handling of equipment in space operations, the simulation of launch and re-entry conditions is not required.

In consideration of the requirements for simulating the conditions encountered in a vehicle system used in assembly or maintenance of major space station components, the simulator shown in figure 4 has been conceived (ref. 3). It provides for suspending three bodies simultaneously so that each body has six degrees of freedom in simulation of undamped motion. The vehicle system is on one suspension system and a space station component upon which the vehicle system operator works is on each of the other suspension systems.

The test subject can be provided with control of all motions of his vehicle and provisions are made for bringing out independent control signals for each degree of freedom so that various configurations of control systems and various vehicle masses can be simulated. Vehicle motions can also be initiated by the application of an external force to the vehicle. The direction and magnitude of such forces are determined by strain gages which pick up torque and force at each of the three gimbal axes. A computer system calculates the velocities and accelerations which would result in space from both the vehicle operator inputs and the interbody forces. Signals are then sent to the appropriate servosystems which, in turn, drive the vehicle at these velocities and accelerations.

The two suspension systems supporting the work components operate similarly to the one supporting the vehicle system in that the forces and torques applied to them are measured and converted into translation and rotation which simulate the motion they would have in the space environment.

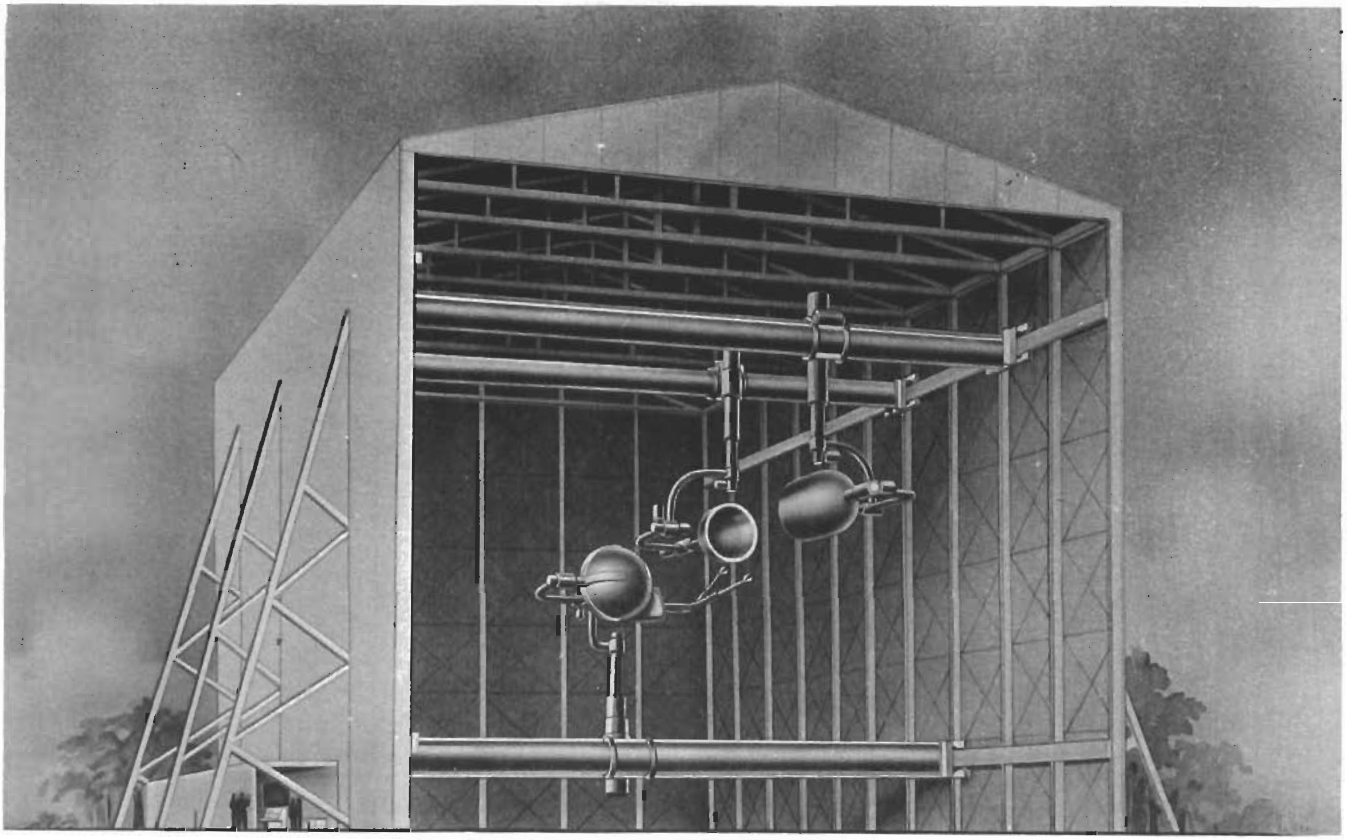

Figure 4. Advanced Flight Simulator Facility

By means of curtains, lights, and projectors the external visual environment can be simulated. A combination of insulation and recordings can provide the proper aural environment.

This simulator would permit development of remote-handling systems and design of space equipment which would be tested prior to launch. Training of operators for the vehicle systems and handling equipment should be invaluable as training of operators for hot laboratory manipulators now is.

In summary, the best remote-handling space system should result from the proper matching of the operator and equipment. One of the best means of achieving this matching is by simulation. Such simulation can hardly be postponed further since the results of studies would be invaluable in designing the first space systems requiring handling, assembly, or repair operations, and in training the men who will operate them in space.

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NORTHROP CORPORATION
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INTRODUCTION

Participation in various system studies concerned with space and extraterrestrial environments has developed within Northrop Corporation, Norair Division, an acute awareness of the requirements for extra-vehicular protection of personnel in these unfriendly environments. This awareness has led to classification of work environments, anticipated tasks, and consideration of remote-handling solutions to special problems. The resulting remote-handling concept runs a gamut of complexity from manned to unmanned devices. The Northrop approach to remote-handling equipment is summarized in figure 1. The individual factors are more completely defined in table I.

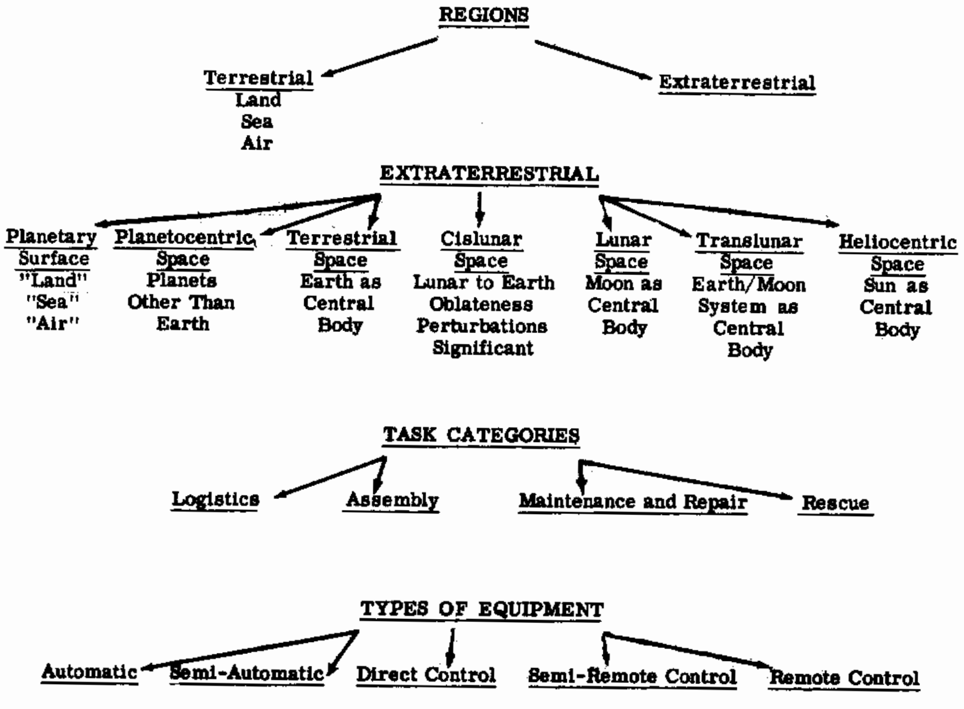

Figure 1. Handling Operations

TABLE I

SPACE HANDLING OPERATIONS

CLASS	DESCRIPTION*	VISUAL ACCESS	REPRESENTATIVE TASKS	TYPE OF ACTUATION**
Ia	Direct Handling - Gloves or Small Tools Work Area within 5 Feet of Operator Probably Most Common Operation in Space (as well as on Earth)	Direct	Black Box Installation and Adjustment-Maintenance and Repair of Skins and Components, Small Cargo Handling	Mechanical
Ib		Indirect	Similar to Ia but with Visual Aid Required due to Darkness or Obstructions	Electrical
IIa	Semi-Remote Operation Direct Tool Control by means of Tool Extension Operating Distance 5 to 50 Feet. Distance Limited by Practical Length of Tool Extension Operation in Isolated Area	Direct	Work with Structures or Components not Accessible or Suited to Class I Handling due to High Temperature, Radioactivity, Electrical Charge, Size, or Fragility	Mechanical
IIb		Indirect	Similar to IIa except that Visual Aid Is Required due to Range, Darkness, or Obstruction	Electrical
IIIa	Remote Operation Tool not Directly Connected to Operator Connection by Radio Link, Electrical Cable, or Hydraulic Lines Distance beyond 50 Feet Operation in Isolated Area	Direct	Low-Precision Operations with Relatively Large Components at Ranges from 50 to 500 Feet. Hazardous Operations - Radioactive, High Temperature, Explosive, Contaminated, Cargo Transfer, Assembly, Positioning	Electrical
IIIb		Indirect	Tasks at Distances too Great for Direct Vision Darkness Obstructed Vision	
IV	Automatic Preprogrammed	Not Required	Self Maintanance, Repair Modification, Logistics, Assembly, Fabrication of Manned and Unmanned Vehicles	Electrical

*Special tools or techniques may be required to handle vacuum welded or partially sublimed components.

**Pneumatic or hydraulic actuation appear to be less desirable due, primarily, to leakage.

PRINCIPAL DESIGN CONSIDERATIONS

The following design considerations for both the overall system, the remote-handling systems, and other subsystems directly affect the requirements for remote-handling equipment:

System Compatibility

Vehicles, subsystems, and components must be designed to be compatible with the handling system to insure that it is possible to:

a. Minimize the number and types of tools required

b. Minimize the number of operations required to install, remove, and replace test and checkout equipment, etc.

c. Minimize the force required for tool effectiveness

Visual Presentation

It is essential that the task area be visible to the operator either through:

a. Direct view, or

b. Visual aids (optical system, electronic system)

Ease of Operation and Maintenance

As with any system for use in connection with space operations, it is mandatory that the system require minimum maintenance and easy operation. This then requires factors of:

a. High reliability

b. Adequate operator restraint for extra-vehicular operations

c. Balanced forces and masses for minimum perturbations

Environmental Protection

Extra-vehicular operations may require special protection devices such as:

a. Sunshades

b. Meteor screens

c. Inflatable structures

d. Furlable structures

PROBLEMS OF EXISTING MANIPULATORS

The human engineering problems associated with remote manipulators are numerous and difficult. Experience generally suggests three major problem areas where research efforts may be most profitable:

Feedback

Many of the manipulator problems may be traced to either a lack of, or an inappropriate, feedback arm or grasping mechanism. In the "natural" setting, an operator may use any one or a combination of his senses to obtain the necessary feedback information. However, when the operator uses existing remote manipulators, the distance to the manipulated object, the intervening manipulator mechanisms, and the "unnatural" control-display relations may place blocks or filters in the feedback channels. Research directed toward removal of these blocks and filters or toward substitution of alternate channels appears promising. Experiments are now being conducted on a method for providing actual feedback for manipulators. Tentative research suggests that back pressures or kinesthetic feedback on control arms may not be required for all the degrees of freedom.

It appears very difficult to give the operator a direct analogy of the qualities of texture and temperature. Assuming that research analysis shows these qualities are necessary, further investigation may be pursued toward using alternate feedback channels. For instance, research has shown the feasibility of using an auditory feedback which gives an indirect indication of texture and temperature.

A great deal of data is available to establish and identify the role of vision and visual feedback in the performance of manual tasks. It is important that the design of manipulators be such that the necessary visual functions are included. Hence, the human factor problem area is not the redefinition of well established visual requirements but rather the determination of the effects of the various restricting factors associated with manipulators, such as distance, optical limitations, etc.

To illustrate, the stereoptic visual function required for various manual tasks is well established. However, stereoptic cues diminish rapidly with distance, become distorted with most optics, and are difficult to maintain with existing stereo-television systems. A series of investigations and experiments has been conducted to develop a stereoptical rangefinder with television which may be applied to providing stereopsis for manipulator use.

The human engineering problem area with respect to other senses is somewhat different from that for the visual or kinesthetic and tactual feedbacks. For these other feedback senses (i.e., auditory, olfactory, etc.), two research needs are prominent. First, more information will be needed on the roles which these other senses actually play in manipulative tasks. Second, more information will be needed on the roles these senses can play. To illustrate the first, it might be asked just how important is it for the manipulator operator to hear a bolt tightening? The second might be illustrated by asking what are the limits to a blind man's auditory information?

Manipulator Strength, Dexterity, and Mobility

This second major human engineering problem area is concerned with the strength, mobility, and dexterity requirements of the man-manipulator subsystems. There are two major phases to determining these human engineering requirements. The first is the need for gathering and classifying basic data through function and task analysis methods. The second is to consider and evaluate alternate methods.

Integration of Manipulator and Manipulated Objects

A third major problem area lies in the integration of a man-manipulator subsystem with the equipment on which it will be used. To date, the manipulator and its operator have had to do the job of handling items designed primarily for manual handling and operation. Because these items were built for manual handling, the design philosophy of existing manipulators has been, to one degree or another, to try to duplicate the physical characteristics of the human. Manipulators built to this philosophy are logically limited at best to human physical limitations, and, in practice, to only a fraction of these limitations. However, by designing system components for manipulator handling rather than for manual handling, the limits of the anthropomorphic approach are removed. Certain functions and tasks could possibly be accomplished more efficiently with man-manipulator subsystems than by current manual methods.

CONCEPTUAL HANDLING DEVICES

The maintenance capsule illustrated in figure 2 would give the operator a direct-handling capability by means of the gloved sleeves or detachable tools. Semi-remote handling capability would be obtained either by attaching remote-handling tools to the ends of the sleeves (in lieu of gloves) or by attaching at the capsule-sleeve interface. Further remote-handling capability would be provided by combining the capsule with an adapter as shown in figure 3.

A capsule of the type indicated would serve as a multi-purpose vehicle providing: (a) protection for personnel engaged in maintenance or repair operations, (b) an emergency escape vehicle, and (c) an emergency rescue vehicle. The capsule would consist of a multiple-walled cylinder equipped with adjustable slippers that move over a rail network on the satellite's exterior. Used in conjunction with the stabilizers, these slippers provide constraint for the capsule during translations along the surface of this satellite and stabilization during maintenance and repair operations. Maneuvering jets are provided for control during the infrequent times when the capsule would be detached from the satellite. Flexible sleeves equipped with couplings for either gloves or special tools would be located below the observation window. A spotlight for illuminating the work area is located on the chest area, and stowage facilities for parts or tools are conveniently located around the surface. The capsule would also be equipped with the systems necessary to support a man for several days. However, these systems are used only intermittently or during an emergency since the parent satellite would supply air, power, and communications through an umbilical connected near the work area.

For external maintenance operation, the occupant of the capsule would be provided with an emergency full pressure suit. The capsule is equipped with rendezvous couplings which are compatible with all of the parent vehicle's external airlocks and airtight doors. When these couplings are retracted the capsule can be taken into the satellite via the personnel airlock for maintenance and servicing of the capsule systems.

Figure 3 illustrates the adaptor concept. Here, the manned capsule shown in figure 2 is mated with the adaptor and is connected to the adaptor's systems by umbilicals. The adaptor is provided with a heavy-duty micromanipulator for handling large masses and with light-duty micromanipulators for performing more precise operations such as tuning and adjusting internal components. The device is supported by four adjustable legs which clamp to the parent vehicle's structure. Free space maneuverability is provided by the capsule's maneuvering jets. Maneuverability over the parent vehicle's structure is accomplished by sliding the adaptor along an external rail network. The capsule can leave the adaptor when the task is completed. The adaptor provides power, propulsion expellant, parts storage, a holding fixture (the heavy-duty micromanipulator) for parts being worked on by the micromanipulators or by the gloved or tooled capsule arms, and other supporting systems such as illumination, test and check capabilities, etc.

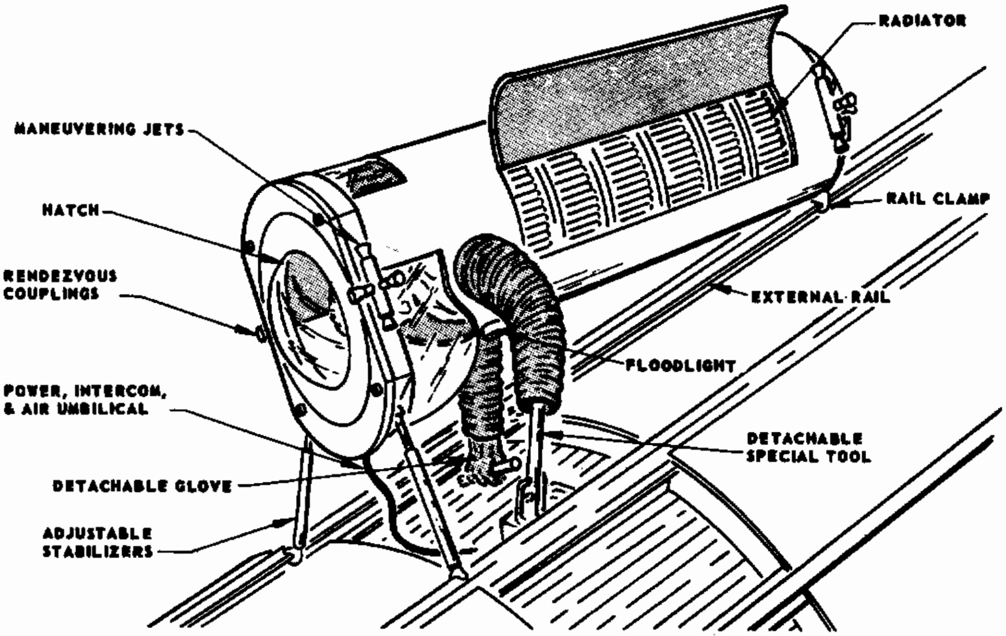

Figure 2. Maintenance Capsule

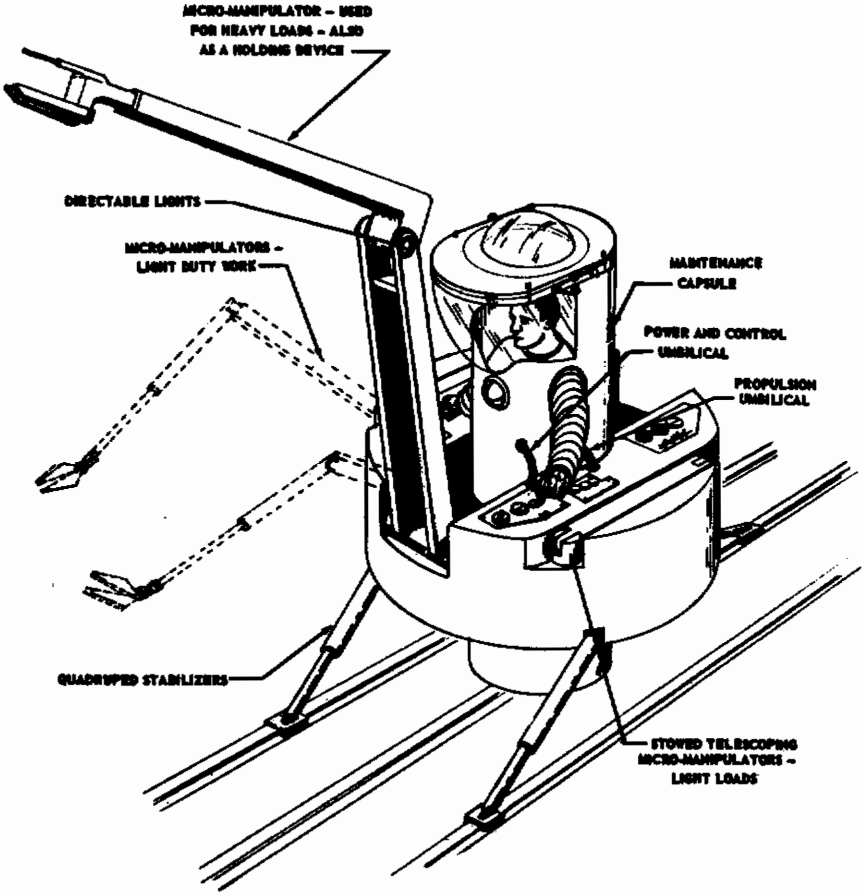

Figure 3. Maintenance Adapter