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# HUMAN ENGINEERING PRINCIPLES OF DESIGN FOR IN-SPACE MAINTENANCE

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BEHAVIORAL SCIENCES LABORATORY  
AEROSPACE MEDICAL LABORATORY

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<p>ASD TR 61-629</p> <p>Aeronautical Systems Division, Aerospace Medical Laboratory, Wright-Patterson Air Force Base, Ohio</p> <p>HUMAN ENGINEERING PRINCIPLES OF DESIGN FOR IN-SPACE MAINTENANCE, by L. D. Pigg, Maj, USAF. November 1961. 16p. 17 refs. (Proj. 7184; Task 718406)</p> <p>Unclassified report</p> <p>Results of research on problems related to human performance of maintenance actions in space systems are reviewed. The interactions of sensory, psychomotor, and motor functions are discussed, along with problems of remote-handling applications in the space environment.</p> <p>( error )</p>	<p>UNCLASSIFIED</p>	<p>ASD TR 61-629</p> <p>Aeronautical Systems Division, Aerospace Medical Laboratory, Wright-Patterson Air Force Base, Ohio</p> <p>HUMAN ENGINEERING PRINCIPLES OF DESIGN FOR IN-SPACE MAINTENANCE, by L. D. Pigg, Maj, USAF. November 1961. 16p. 17 refs. (Proj. 7184; Task 718406)</p> <p>Unclassified report</p> <p>Results of research on problems related to human performance of maintenance actions in space systems are reviewed. The interactions of sensory, psychomotor, and motor functions are discussed, along with problems of remote-handling applications in the space environment.</p> <p>( error )</p>	<p>UNCLASSIFIED</p>
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**PROJECT No. 7184  
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**AERONAUTICAL SYSTEMS DIVISION  
AIR FORCE SYSTEMS COMMAND  
UNITED STATES AIR FORCE  
WRIGHT-PATTERSON AIR FORCE BASE, OHIO**

## FOREWORD

This report was prepared by the Maintenance Design Section, Human Engineering Branch, Behavioral Sciences Laboratory, in support of Project 7184, "Human Performance in Advanced Systems," Task 718406, "Design Criteria for Ease of Maintenance," with Major L. D. Pigg as task scientist. This paper was presented at the Joint National Meeting of the Institute of Aerospace Sciences and the American Rocket Society, June 1961, Los Angeles, California.

ABSTRACT

Results of research on problems related to human performance of maintenance actions in space systems are reviewed. The interactions of sensory, psychomotor, and motor functions are discussed, along with problems of remote-handling applications in the space environment.

PUBLICATION REVIEW

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## HUMAN ENGINEERING PRINCIPLES OF DESIGN FOR IN-SPACE MAINTENANCE

### INTRODUCTION

Successful space flight will require extremely reliable operation of the space vehicle systems. Presently available components do not have inherent reliabilities sufficiently high to satisfy the overall requirement for space flight. Thus, a major effort toward system reliability improvement is indicated.

This effort can take one or more of at least three courses: components redundancy, components reliability improvement, or in-flight repair by crewmen. As a practical matter, efforts in all three directions appear necessary. Some redundancy in the form of parallel units for critical elements is probably unavoidable. Weight restrictions dictate a limit to redundancy, however, and complementary actions must be taken. Components reliability improvement can be brought about through special development efforts, but here, too, there are practical limits. Thus, the repairman is called into the system. He repairs the element which has failed while its redundant backup element is in operation.

In the opinions of several writers, using man in this maintenance function constitutes the best hope for achieving the required reliability of space systems. Perhaps the case is best represented by McRuer, Ashkenas, and Krendel (ref. 14) who state "...with a small stock of spare modules and parts, and a man, an actual physical system with only one or two parallel channels can approach an effective system with much more redundancy. Thus, a prime human role in space will be that of failure detection, replacement, and repair."

Information on the general problem of design for maintenance in space is limited. Much research must be accomplished before effective utilization of man in this role of great potential importance can be realized. This research must cover at least the problems of intra- and extra-vehicular maintenance operations, remote-handling applications in space maintenance, and integrated systems design for maintainability in space. This paper describes results of research efforts directed toward solution of some of these problems by the Human Engineering Branch of the Aerospace Medical Laboratory at Wright-Patterson Air Force Base, Ohio.

## DESIGN CRITERIA FOR MANUAL MAINTENANCE

Several studies have been carried out to determine the effects of weightlessness and frictionlessness on sensory processes, basic psychomotor performance, manual application of forces, and discrimination and handling of inertial objects, including stores, components, and tools. These studies have made use of zero-g aircraft, or air-bearing devices which support man or objects in near-frictionless states for indefinite time periods, to simulate the weightless-tractionless aspect of the space environment.

### Sensory Performance

Many intriguing questions about man's performance in space concern the responses of his sensory processes to the environmental factors of weightlessness, isolation, stress, etc. Most of the answers will come only after man has successfully journeyed into space. Some work has been done and most of it is generally well known. Two studies are worth mentioning here.

#### Visual Acuity:

Increased positive and negative accelerative forces produce losses in visual acuity (ref. 17). To see if weightlessness would also affect visual acuity, subjects were tested for binocular and monocular near and far vision on two types of acuity targets while they were exposed to zero-g aboard a C-131 aircraft (ref. 15). Statistically significant decrements were found for zero-g scores by comparison with control scores in 1-g flight. Differences in accommodation and types of targets did not significantly affect the results. The average decrement was the equivalent of a 6% increase in visual angle of targets at threshold legibility. For ordinary purposes of vision this is not of practical consequence.

#### Vestibular Functions:

The effect of aircraft-produced weightlessness on goldfish, pigeons, and animals was studied to see whether the so-called gravi-receptors of the vestibular region of the inner ear are indeed sensitive to acceleration (ref. 11). The goldfish assumed unusual positions, even inverted, during weightlessness. Pigeons did not demonstrate the postural reflex which, under 1-g, causes compensatory head movement in response to body rotation. The righting reflex of cats was noticeably absent. These results only tend to verify what has frequently been noted by human subjects during weightlessness: that spatial disorientation is apt to occur.

### Sensory-Motor Performance

We are accustomed to lifting and moving things by overcoming the existing pull of gravity on both our limbs and the objects we handle. We learn very early to judge the weights of objects and to predict their movements by the forces in our limbs as we handle them. In a weightless environment, there is no gravitational force to overcome and even the smallest force will accelerate a free-floating object. Thus, man's judgment and effectiveness in the handling of objects may suffer in the space environment.



#### Discrimination of Mass:

One interesting question concerns man's ability to discriminate differences in mass of weightless objects. To provide an answer, a laboratory study was carried out to compare man's ability to discriminate small differences in mass with his ability to discriminate differences in weight (ref. 16). Four weight series were used, each consisting of a standard (1000, 3000, 5000, or 7000 grams) and nine comparison stimuli. Judgments for mass differences were made with the same weights supported by compressed air on an air-bearing table in simulation of weightlessness. Results show that difference thresholds (the amounts by which two stimuli must differ to be perceived as different at least 50 percent of the time) are approximately twice as large for mass as for weight, and, further, that they are approximately proportional to the mass of the objects handled. This proportionality is also true for weight for which the difference ratio is generally found to be .05. Thus, the difference ratio for mass is approximately .1; i.e., for two objects to be perceived as different in mass, they must differ by 10 percent. The difference in discriminability of mass and weight is related to man's inability to achieve standard accelerations and movements of objects having only mass.

#### Positioning of Objects:

In other studies (refs. 12, 13), performance in positioning of "weightless" objects was measured to see if loss of the cue of gravity would affect speed and accuracy of handling operations. Subjects positioned objects of varying mass through different distances and directions while the objects were airborne over an air-bearing table. Both fixed subjects (standing) and tractionless subjects (seated on an air-bearing platform) were used.

For the fixed subjects, change in object mass produced no pronounced effect, but changes in both distance and direction led to significant changes in performance. Response time increased while accuracy decreased with distance. Response time was less for near-to-far movements than for left-to-right movements, although accuracy was greater for the latter. Thus, in this case, the usual correlation between speed and accuracy was not found.

For the tractionless subjects, the results differed primarily in that change in mass did produce significant differences in response time, with heavier masses involving longer response times. Also, by comparison with fixed subjects, tractionless subjects had significantly poorer performance in terms of accuracy. However, response times were shorter—a function of the shorter time available for response in the dynamic action-reaction condition.

#### Operation of Switches:

In another study (ref. 11), subjects operated different types of switches to turn lights on and off as they were flown through zero-g trajectories. Push-button, toggle, and rotary switches were paired with a master switch so that accuracy could be checked and comparisons in terms of speed of operation could be made. Small but statistically significant decrements were found in speed of operation of all three sets of switches in the weightless environment by comparison with control performance at 1-g. The toggle switch showed the greatest decrement, the rotary switch set the least. Speed of operation was greatest with the push-button set under both 1-g and weightlessness.

**Motor Performance**

As for pure motor performance in the space environment, two studies provide useful data (refs. 9, 10). In these, subjects riding on an air-bearing platform, thus tractionless, were asked to apply maximum push-pull forces at various distances and angles from a single handhold.

**Torques:**

For certain handhold angles the average maximum continuous force which a man could exert was equivalent to a torque of 2.5 pound-feet--that is, a push or pull of 2.5 pounds at a distance of 1 foot from the handhold, 1.25 pounds at 2 feet, etc. These are definite limitations on design of units requiring application of force for more than 3 seconds by a worker using only a handhold to retain his position at work.

**Impulses:**

Also measured was the ability of tractionless subjects to apply impulses while anchored by a handhold 2 feet from the point of application of force. A 40-pound push force could be applied effectively for only 1/2 second, while lesser forces down to 5 pounds could be applied for longer periods up to 1 second. The limitation of the impulse is determined by the movement of the subject away from the point of application as a result of the counteractive force. Related to this reactive movement was the interesting demonstration that it is possible for a subject to seat an object against a frictional force by using a high-force, short-duration impulse, and then bring himself to rest while holding onto the object, without unseating it, by applying an opposite force (less than the frictional one) of longer duration.

**Handtool Operations:**

Qualitative observations have been made of handtool operations by a free-floating man in the weightless environment of the aircraft, where six degrees of freedom are possible (in contrast to the three degrees of movement available on an air-bearing platform). Work without a handhold or other means of attachment was impossible. Even with a handhold, the strength of the wrist was not sufficient to compensate for the reactions to the forces exerted in simple handtool operations; thus, awkward body movements resulted.

**DESIGN CRITERIA FOR REMOTE MAINTENANCE**

Research is also underway to establish human engineering principles governing design and use of remote-handling and associated equipment for space operations. The role of such equipment is apparent in connection with the tasks accomplished outside the space vehicle where, because of the quantity and severity of physical hazards, it is improbable that man will be able to work effectively without some means of extending his perceptual and physical skills beyond a restrictive amount of protective shielding. Remote handling will allow man to work beyond such shielding in areas of high radiation, near or total vacuum, extremely low temperature, etc. Thus, many current space proposals include ideas of use of remote manipulative equipment, ranging from the simple to the complex, for many jobs in places where man cannot go without special protective devices (which hamper his mobility and action, and may themselves include remote-handling appendages).

### Task Variables

Among the tasks for remote handling in space will be assembly, disassembly, and maintenance of space systems, including inspection, repair, servicing, and checkout; experimentation, including exploration, sampling, and testing; transfer of personnel, supplies, and equipment; and emergency operations, such as escape and rescue (ref. 5). These tasks have much in common with remote-handling tasks involved in ground-borne operations. Thus, many of the research results relating to these tasks will apply in design for remote handling in space.

#### Task Distance:

The effect of this variable on performance of a manipulative task was investigated with a CRL<sup>®</sup> Model 8 Master-Slave Manipulator (ref. 2). Performance time increased significantly as the task was moved from a position 7 feet from the operator's eyes to 9 feet, and again as it was moved to 11 feet. This reflects the loss in visual resolution and depth perception accompanying increased distance. At distances of 100 feet or more, telescopic or television monitoring is necessary for practical purposes.

#### Object Size:

The effect of this variable was investigated in a task in which different sizes of hexagonal nuts were removed from bolts (ref. 3). Performance time was not significantly changed as nut diameter was increased from 3/4 inch to 2-1/4 inches (the practical limit for the manipulator slave hand).

#### Angle and Height of Task Display:

These variables were studied in connection with the nut-removal task described above. For the standing operator working at several different task angles, significantly better performance resulted when tasks were presented at a working height 45 inches from floor level, by comparison with both lower and higher working heights. Without regard to task height, performance was better in the 45° to 65° range of task angles measured from the horizontal plane. The two variables were found to interact, however, so that horizontally oriented tasks were performed best at the lowest height and poorest at the highest working height. Vertical tasks were performed best at intermediate heights.

### Equipment Variables

Many remote-handling problems relate to the design of the equipment itself. Much attention has already been given to the effects of change among the many variables of design of manipulators and accessories (ref. 5). Sensory feedback (tactual, kinesthetic, visual, and even auditory), movement ratios, force ratios, power provisions (mechanical, hydraulic, electrical), and auxiliary controls, to name a few, have been studied. Two studies of this nature are reported below. But first it is worthwhile to look at the effects of the manipulator itself on human performance.

#### Remote versus Direct Handling:

Remote handling is employed at a price. By comparison with direct manual performance, use of mechanical master-slave manipulators generally reduces efficiency

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to a significant degree. To calibrate this factor, a standard manipulative task was performed with both modes of handling in an experimental setup which controlled for extraneous effects such as practice and sequence of test (ref. 2). Operators of the CRL Model 8 manipulator took 6 to 10 times longer, depending on task distance, to perform the task than did direct handlers. The factor of 6 was found for the 7-foot task distance, the factor of 10 for the 11-foot distance. The ratio of 8 to 1 (found at 9 feet) was most representative of remote tasks performed at the modal distance.

#### Weight Discrimination:

Studies were conducted to determine the effect of remote handling on ability of subjects to make both absolute and differential judgments of weights (refs. 6, 7). By comparison with direct handling, remote handling produced absolute estimates which were higher and more accurate on the average but more variable. There was less tendency for remote estimates to be influenced by immediately preceding handling operations (contrast effect). Difference thresholds, the amounts by which two stimuli must differ to be perceived as different at least 50 percent of the time, were nearly doubled with remote handling. Thus, sensory feedback is attenuated by remote handling so that two objects differing less than 8 percent in weight cannot be effectively discriminated.

#### Mass Discrimination:

Since objects in space do not have weight, it is useful to know what the difference threshold for remotely handled masses will be. The discrimination study was repeated (ref. 8), using objects supported by compressed air (over the air-bearing table mentioned previously). It was thus a mass-discrimination study. The difference threshold in this case was 23 percent, more than double the difference threshold for remotely handled weights. A summary of results of the several discrimination experiments shows that loss of weight as a cue leads to doubled difference thresholds, which are, in turn, doubled by remote handling:

<u>Basis of Discrimination</u>	<u>Type of Handling</u>	<u>Difference Ratio</u>
weight	direct	.05
	remote	.08
mass	direct	.10
	remote	.23

#### Mode and Rate of Indexing:

Mechanical master-slave manipulators have auxiliary devices by which the slave hand is moved to areas not reachable by normal articulation. This is called indexing. It is normally controlled by a hand-operated, two-way switch. Performance with the hand switch was compared with performance with a foot-operated switch on a task requiring indexing (ref. 4). Three representative rates of indexing were used. No advantage in task speed was found for either mode of indexing, but fewer errors (dropping objects, indexing in the wrong direction) occurred with the foot control. There was also evidence of faster learning (to an asymptote of performance time)

with the foot control. These results were not altered by change in rate of indexing, even though such change was shown to affect speed of performance significantly (higher rate--shorter task time) for most tasks. For tasks involving only short indexing distances, there was no advantage in faster indexing.

#### Color Coding of Jaws:

In another study, involving intricate manipulations of small objects, different colors were used for the slave fingers to see if task performance could thereby be improved (ref. 2). Significant differences were not found. Thus, color coding of the remote-handling equipment itself is not indicated. More appropriate use of color to improve remote-handling performance may possibly be made in design and layout of the task to be performed.

#### Operator Variables

As in any task requiring skill, individual differences exist in remote-handling performance. These can result from differences in inherent manual dexterity, coordination, visual acuity, depth perception, and other such factors. Operator screening is a means of controlling them. Beyond this, there are still many other operator variables which affect performance. Two have been studied:

#### Practice:

Naive subjects were used for remote performance of a block-manipulation task. Performance time decreased to a practical asymptote within just a few trials, indicating that beginner operators adapt to the grosser aspects of the master-slave manipulator with little difficulty (ref. 2). For satisfactory performance of more intricate tasks, several hours of training may be required.

#### Seated versus Standing Operators:

A study was conducted to determine the extent of limitations upon the work range of the manipulator resulting when the operator is seated (ref. 1). This was thought to be a way of approximating the effects of confined quarters which may exist in space applications. Contours of effective performance were progressively reduced in area as the plane of the task was lowered to the level of the knees and below. In general, the range of effective performance for the seated operator was approximately one-third the range for an unrestricted standing operator.

### FURTHER RESEARCH NEEDS

This paper deals only briefly with results of a very limited program of research on problems related to human performance of maintenance actions in space systems. A great number of other research efforts pertinent to these problems are being carried out by many different agencies. Success in manned space operations will depend a great deal on the success of these and future efforts.

While the total, necessary, additional, human factors effort cannot be specified, further work which should be done to extend the usefulness of the results reported in this paper can be identified.

Additional research is needed on design criteria for extra-vehicular operations in space. Design information, principles, and procedures of operation for all equipment used in or for maintenance in space must be developed and validated. Included in this research are human engineering principles of design and use of hand-tools; of environmental protection devices, including partial shielding; and of maintenance aids, such as checklists, handbooks (or information storage devices), and test equipment.

Additional research is also needed to develop basic remote-handling concepts, and to establish criteria for comparing and evaluating different types of remote-handling systems with respect to their usability in the space environment. Solutions to perceptual problems connected with remote operations in space are needed. Problems of remote visual access, including use of closed and open circuit television, depth and movement perception, illumination, glare, contrast, and tactual and kinesthetic feedback are representative.

These are just a few of the many considerations important to effective maintenance operations in space systems. Research is underway to provide needed answers for many of the questions. Much more must be undertaken to satisfy the overall need.

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