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MAN-SYSTEMS REQUIREMENTS FOR THE CONTROL OF TELEOPERATORS IN SPACE

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Abstract

The microgravity of the space environment has profound effects on humans and, consequently, on the design requirements for subsystems and components with which humans interact. There are changes in the anthropometry, vision, the perception of orientation, posture, and the ways in which we exert energy. The design requirements for proper human engineering must reflect each of the changes that results, and this is especially true in the exercise of control over remote and teleoperated systems where the operator is removed from any direct sense of control.

The National Aeronautics and Space Administration has recently completed the first NASA-wide human factors standard for microgravity. The Man-Systems Integration Standard, NASA-STD-3000, contains considerable information on the appropriate design criteria for microgravity , and there is information which is useful in the design of teleoperated systems. There is not, however, a dedicated collection of data which pertains directly to the special cases of remote and robotic operations.

This paper deals with the design considerations for human-system interaction in the control of remote systems in space, briefly details the information to be found in the NASA-STD-3000, and argues for a dedicated section within the Standard which deals with robotic, teleoperated and remote systems and the design requirements for effective human control of these systems in the space environment, and from the space environment.

Introduction

The history of manned space flight is filled with the scientific and exploratory accomplishments of humans and demonstrations of our productivity in the orbital environment. During the Skylab era, were it not for the corrective measures taken by the first manned mission to Skylab, the program would have been lost. The several satellites which have been recovered, repaired and returned to orbit by Shuttle crew members is testimony to the key position that humans hold in carrying out our successful space program. The Apollo Program sent men to the Moon and returned them, and the results of their exploration, as well as their impressions of our planet from a new vantage point.

In the next decades, we will return to the moon and venture out to Mars. We will orbit the Earth in a permanently occupied Space Station, and begin the colonization of our solar system. We will do all of this based on our experiences and successes of past missions and our desire to comprehend the Universe around us.

The lessons and legacies of our manned space flight experience, space systems research and human productivity in space have been compiled in the NASA-STD-3000, Man-Systems Integration Standard, the first NASA wide design guide for man-systems in space flight. This four volume set of design guidelines presents the design considerations and requirements for the effective employment of humans in space. The table of contents reflects the human engineering issues which must be addressed in order to support humans in space, both inside of spacecraft (intravehicular activity) and outside of spacecraft (extravehicular activity). In point of fact, the two precedent human engineering guidelines for space flight programs were divided along the EVA and IVA roles in space. The MSFC-STD-512A is a very detailed treatment of the IVA issues, while the JSC 10615 dealt with the EVA design considerations and requirements. The contents and philosophy of these two useful guidebooks have been combined and superceded by the NASA-STD-3000. But is the support of humans in space the only way to effectively conduct space exploration and operations?

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Many of the research programs that are sponsored by NASA in the areas of robotics and teleoperation suggest that direct human presence and intervention are not the only means by which we can explore and manipulate the space environment around us. The Marshall Space Flight Center has conducted research in teleoperated systems since the late 60's (1), The Jet Propulsion Laboratory has developed and launched numerous unmanned explorer spacecraft and the Orbital Maneuvering Vehicle is being developed to augment the role of humans in space without exposing them to the hazards and risks of the space environment. The Goddard Space Flight Center is developing the Flight Telerobotic Servicer for remote operations and the Space Station will have a Mobile Servicing Center for the conduct of remote activities at the Space Station. But what of the human operators who will be responsible for the management and operation of these teleoperated and robotic systems? Where are the design criteria which we will employ in the effective integration of human capabilities and those of machines for robotic space operations?

Background

During the definition stages of the Man-Systems Integration Standard every effort was made to identify the categories of experience which we had gained over the past twenty-five years of human space flight. The organization of the standards follows very closely the organization of conventional human engineering and applied psychology texts, but the bibliography and research literature on which the standards are based is unconventional, coming principally from space flight data files and reports. Consequently, we find subject matter titles such as vision, anthropometry, human performance, grip strength, etc. filled with data which is not familiar to human factors specialists who deal only with Earthly design concerns. Alteration of posture, visual capability, spatial orientation and biochemical components of the human are a few of the significant differences experienced as the result of space flight and the effects of microgravity.

During the development of the Man-Systems Integration Standards, there was considerable discussion concerning the treatment of extravehicular activity design data and requirements. "EVA is a special set of operations requiring a special treatment in the development of design standards", was one of the arguments. Certainly, the fact that the human assumed the shape of the space suit, that without the space suit there could be no EVA, and that the boundary of the space suit was the envelope of design interest, were all radically different factors than those which have to be considered for IVA, or shirt sleeved operations conducted in a pressurized space craft. On the other hand there was the argument for an integrated design standard which dealt with space flight issues as though there were not significant differences among the several classes of activities. "Put the EVA requirements and considerations in a sub-paragraph of the topic of interest", went the argument, assuming that space flight activities are space flight activities.

The recognition that EVA is a significantly different means of conducting space operations is evident in the dedicated chapter detailing EVA design requirements in the NASA-STD-3000. The organization of this chapter follows the organization of the standard itself, but the details pertain to the special design constraints associated with EVA. So, the argument for a separate chapter prevailed, but another argument was lost, that for a chapter dealing with the special design constraints associated with robotics and teleoperation as a means to carry out space operations.

Space Automation, Robotics and Teleoperation as a Special Class of Space Operations

The technology to perform remote operations with humans as the primary controller or supervisor is well demonstrated on a daily basis in chemical processing plants, electricity generating plants, undersea exploration and operations and in steel processing facilities to cite only a few examples. Human operators visually inspect and monitor, manipulate and order, control movement and orientation of remote systems as though they were actually in the remote environment. To do so requires special technology and specific information be made available to the operator. The content and format of this information and the control and display requirements to manage this technology are not always the same as they are in a conventional, direct management work situation. The support requirements for remote vehicles are also different from those which are managed directly by humans. Just as handrails, handholds and work restraints are required for the conduct of EVA, teleoperated systems require special design consideration to support the man-machine symbiosis. The issue is, where do we go to find these special design considerations and requirements for remote space operations? If both remote operations and space operations are special classes of activities performed by humans and machines the question then becomes, is there a human engineering design data base for remote space operations?

Remote Vision

Using direct visual apprehension, the human is able to detect targets as small as .01 arc minutes, able to perceive variation

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among hundreds of colors, estimate distances using stereoscopic, as well as monoscopic, cues and detect motion in the visual field. The current state of video technology does not take full advantage of the human's visual capability and, consequently, some design compromises have been made which have been shown to have a negative effect on system performance. Black and white video offers higher resolution than current color television, but at the expense of loosing the advantage of the information conveyed by colors in the remote scene (2). Stereoscopic television systems provide a means of perceiving depth in a visual display, but usually at the cost of reduced frame rate, reduced field of view, constraints on head movement or reduced luminance (3). Even in the best systems, sensor and display technology combine to limit the resolution of the remote scene to 3 or 4 arc minutes, or require a prohibitively large bandwidth for signal transmission, especially for space applications. And the field of view that is available from most display systems is greatly less than the normal field of view that we use to comprehend the environment on a day-to-day basis.

On the other hand, video technology permits us to combine graphical data with visual scenes, augment displays with computer generated information, build synthetic displays which can be used to rehearse an activity before executing it, focus on a specific point in the visual field, enlarge or reduce the field of view, greatly magnify an object, and actually insert a visual probe in spaces where we would otherwise be unable to see. In some systems, multiple cameras and displays can afford a forward, as well as a backward, view of the remote environment. And in others, we can enhance a visual scene through computerized reconstruction to provide a representation of the remote environment that would otherwise be meaningless. There are new technologies such as fiber optics, head up displays, helmet mounted displays and virtual image displays which can be employed in the control of remote systems, and we are coming to understand how and where this technology can be effectively used. What is not fully understood, from a functional standpoint, are the effects on operator performance that this technology has. What is lacking is a description of what we do know about human performance and remote vision and system performance as they are applied to robotic space applications.

Remote Manipulation

Through the use of his hands, the human is able to sense small forces or exert gripping forces for a short period in excess of 100 pounds. Using direct touch, the operator can manipulate objects that are out of view. He can make quick and delicate motions to change items in the direct environment, or make quick and forceful motions and crush a concrete tile with his fist. The operator can sense differences in mass by comparing two objects held in his two hands. And by picking up a tool, he can multiply his capacity to manipulate and alter the environment within his reach. The ergonomics of manual dexterity, fatigue, operating errors, and the tactile senses are well studied and documented in conventional human engineering texts and design guidelines. The human requirements for control and management of remote manipulation are not so well understood or documented. For space operations there is not a formal body of knowledge to which a system designer can turn for design requirements and guidelines.

As a means of manipulating and changing the remote environment, space teleoperators are usually envisioned with a manipulator arm, at least one and more often with several. The terminal effector is generally drawn as a clamp or multi-fingered hand, or in the case of a teleoperated Mars soil sampler, a simple scoop. The Shuttle Remote Manipulator System (RMS) has a terminal effector which can accept only specially prepared grapple fixtures in order to handle remote payloads. More advanced manipulator systems for space, such as the Flight Telerobotic Servicer and the Orbital Maneuvering Vehicle are being designed with more manipulating capability and a more flexible terminal effector than are available on the RMS. However, the design requirements to take full advantage of the capabilities, and avoid the limitations, of the human operator in remote manipulation are not yet fully developed.

The minimum detail required to support the design of systems for remote space manipulation will require an understanding of the effects of employing a particular end effector, the type of articulated arm, the control algorithm and the control devices used by the human to accomplish the remote task. A significant change in any of these components has been demonstrated in the laboratory to have a change in the overall system performance (4).

Design considerations and requirements for remote space manipulation should include the use of general purpose effectors such as grasping fingers, opposed clamps, parallel jaws and other, near anthropomorphic approaches. The design considerations for specialized effectors such as terminal tool kits, inflatable end effectors, tactile probes, and capture and docking devices should be detailed in a design handbook. Each time we want to employ a remote manipulator end effector system, we should not have to design it from scratch and for only one mission or application, but rather we should be able to refer to a class of demonstrated designs and the effects they have on human performance.

As we move up the manipulator from the effector, we will want to know the consequences of employing a particular style and design of manipulator arm. There are demonstrated performance differences among classes of arms with respect to various tasks. Telescoping arms, for example, are commanded to a specified point in less time than are multi-jointed, articulated arms (5). This might be useful information in the design of a capture and docking device for space teleoperators, where the teleoperated arm is required to reach out and get a secure hold on a specific capture fixture on a satellite. The system designer might want to know the performance differences between the control of anthropomorphic and non-anthropomorphic arm designs, if there are any. And what are the effects on the operator of adding more degrees of freedom to an articulated arm? Can the more complex design produce a higher level of performance, or does the operator become confused in the control of multiple degrees of freedom and consequently, overall system performance declines?

One of the recurring issues in teleoperated space systems is the number of arms that one operator can and should control. One way to avoid the design solution of providing the maximum imaginable number of arms required to perform the task and then forcing the operator to contend with the simultaneous control of these is to include the human performance design requirements in the system design, but where do we look for such requirements?

Between the physical manipulator with its end effector and the human operator of a space teleoperator there is the control algorithm. What approaches to control software produce the best results for space teleoperation? Do operators perform a class of tasks better when they have tip position control, or joint control, or does it make any difference? Is system performance changed when the software executes specified routines rather than having the operator have to perform them? At what rates should a control algorithm permit a manipulator to execute a task if, at any time, the intervention of the human operator is likely to be required to manage unforeseen circumstances? The designer of space teleoperators should be able to consult a design guide which addresses these issues, if not answer them.

The control system by which the human operator manages the remote manipulator in space might be a manual controller, or a voice controller. The manual controller might be one or two handed, a joystick or trackball, exoskeletal, replica, force reflecting or position commanding. But which is better and which is best?

A serious attempt has been made by the National Bureau of Standards to quantify the performance criteria for measuring manipulator capabilities, and to standardize the devices and methods used to evaluate manipulator systems, so the data bases are available or under construction (6). It is really a matter of getting the information into the hands of the design engineers in a format that is useful, and with full recognition of the human operator as a central feature of the teleoperated manipulating system.

Workstation Design for Remote Operations

When we consider the design of workstations for remote space operations we are confronted with two populations of operators, those who operate from the microgravity environment and those who operate from ground based control stations. They are exclusive populations in terms of anthropometry and operational requirements. The designer of teleoperator workstations should have the advantage of what has been learned about the design constraints which apply to both of these populations. There has been significant research and design work done for both the terrestrial and the microgravity workstations, consequently the issue of work station design is a less pressing one if the designer is familiar with the requirements which suit both populations.

Again, the required study has been accomplished. We know how to design Earth based workstations which complement the operator's ability to perform remote tasks, and we know how to take advantage of the microgravity environment, its effects on human performance, and design workstations to accommodate to these factors. What is needed is the incorporation of these data in a dedicated chapter of the Man-Systems Integration Standard which deals with teleoperation and automation. Here the designer could review the postural and anthropometric changes that take place as a result of living and working in space, the increase in stature and the effective decrease in operational posture. The designer could review the effects on vision and visual perception which accompany an environment which does not filter and refract light through a thick atmosphere. He could review the requirements for operator restraint at a workstation and determine if the restraints would accommodate a spring loaded, force reflecting hand controller without having it push the operator away from the workstation as control forces, and equal and opposite reactive forces, are transferred to and from the hand controller.

System Induced Factors

Working from Earth to control a space based servicing teleoperator may involve distances of only 400 or 500 kilometers. However, the transmission and relay of commands and feedback on such low Earth orbital exercises may be as much as 2 or 2.5 seconds as a function of network delays. With the use of significant ground networks it could be even more. What are the effects on the human operator of having such a delay in the control loop? Are the effects different for different periods of delay? Are there differences in system performance when the delay is random and unpredictable, a function only of the network cycle times? Are there design solutions which have been shown to be effective in compensating for control loop delay? Control loop time delay has been the subject of several recent NASA programs, and will continue to be a topic of interest as more robotic space vehicles are placed in service (7). The issue remains, however, as to the best means to provide the research findings and design considerations to the system designer. We should not expect, as information consuming and processing animals, that every designer should be aware of the study results concerning all of the subsystems with which the human is required to interact with during a teleoperated mission. These data should be made available in a centralized data base detailing the response of humans to remote systems technology.

Summary and Invitation

Each year the NASA-STD-3000 is reviewed by a government and industry advisory group, and critical information is added, modified and edited to make the standard more reflective of the changing technology, new research findings and program requirements. The NASA Johnson Space Center is responsible for maintaining the critical comments and reviewing them for incorporation in the standard. These comments are classified into four categories as follows:

1. Introductory, explanatory and clarifying statements which introduce the topic to the reader. For a space teleoperations section this would include a definition and discrimination of teleoperators, robots, artificially intelligent machines, automata and the like. It would provide a description of the general system to include the orbiting or roving machine, the relay and transmission system, the effectors on the machine and the human operator as an element in the control loop.

2. Design considerations and comments. These are the salient points to consider in the design of a human operated system, although the considerations may not give strict rules to follow. For teleoperated systems, the design considerations might include the degree of telepresence appropriate to the control system, the variety of hand controllers which are available for control of teleoperators and a general discussion of the differences among them. In this section the issues of time delay, color coding display formats and arrangements would be dealt with as items which the designer must take into consideration as he or she begins to define the remote system to meet his or her special systems' requirements.

Very often the information contained in the considerations section is more important than information contained in other of the sections, but because it serves as a menu of options, it is usually not detailed and specific enough to tell the designer what to do, just what to consider.

3. Design requirements is the third section for each topic in the standard. It is in this section where engineers and designers find the detailed requirements which must be met in order for the system in question to meet the demands made on human operated space vehicles. Where possible, the requirements are specified in quantitative terms, usually within a design range. Variations from any of these requirements calls for a review and approval of the design variation. For space based teleoperators the requirements might call for a fixed period of time which an operator can work without relief, or state that control inputs shall not be capable of accidently damaging the craft, or that display resolution shall be greater than 1 arc minute. They would probably state the minimum display rate, signal-to-noise ratio and contrast and display brightness. Concerning the use of flight controllers and manipulator controllers, the requirements would specify force and torque limits and the number of degrees of freedom which can be controlled by an operator. The requirements for space teleoperators will probably seem overly restrictive, but they will ensure against system failure and damage to adjacent structures. The requirements are those items which must be satisfied in order to ensure an appropriate allocation of authority and autonomy between the human and the machine.

4. Design examples and solutions is the fourth section of each of the topics covered in NAS-STD-3000. Here, proven space designs are presented, not as the answer to a designer's dream, but as historically successful solutions to problems encountered in space systems. For space based teleoperators and robots this section would include the Mars lander, the Soviet lunar rovers, the Shuttle Remote Manipulator System and other extant examples. It might also supply design solutions from very near term programs such as the Flight Telerobotic

Servicer or the Orbital Maneuvering Vehicle if they advance the state of the art or understanding beyond that provided by historical missions.

As the role of teleoperators and robots becomes more wide spread in the space environment, and as NASA and the Department of Defense come to rely on them more, there will be a clear requirement to develop a dedicated human engineering design standard for telerobot systems. Those of us who are interested in seeing the effective application of this technology can contribute our concerns and knowledge to such agency wide standards as NASA-STD-3000. First, we can request to be included in the next Government and Industry Advisory Group meeting, and second, we can send recommendations concerning the incorporation of man-systems/remote systems data into the existing standard. The Johnson Space Center is responsible for maintaining the Standard, and comments and considerations can be forwarded to Mr. Cletis Booher, SP3/Man-Systems Integration Standards, NASA-Lyndon B. Johnson Space Center, Houston, TX 77058. It is hoped that in the next few years, through the efforts of participants in symposia such as SOAR and the Robotics Industry Association that we will be able to define and contribute a body of knowledge which will encourage the application of automata, robots and teleoperators to the operations of our space program.

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