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SIMULATION OF THE HUMAN-TELEROBOT INTERFACE ON THE SPACE STATION

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INTRODUCTION

The Space Station is a NASA project which, when completed in the mid-1990s, will function as a permanently manned orbiting space laboratory. A part of the Space Station will be a remotely controlled Flight Telerobotic Servicer (FTS). The FTS, a project led by NASA's Goddard Space Flight Center, will be used to help assemble, service, and maintain the Space Station and various satellites. The use of the FTS will help ensure the safety and productivity of space-based tasks normally accomplished by astronauts performing outside the pressurized spacecraft. For the short-term, control of the FTS will be dependent primarily on the human operator. Since the human operator will be a part of the telerobotic system, then it is important that the human-telerobot interface be well-designed from a Human Factors perspective. It is critical that the components of this interface be designed so that the human operator's capabilities and limitations are best accommodated for within the structure of specific task requirements. To emphasize the importance of a well-designed human-telerobot interface, one study found that simply the selection of an appropriate control device, based upon the operator's capabilities and the requirements of the task, can more than double the productivity of the telerobotic system (O'Hara, 1986).

With the system development process becoming more complex and expensive, more emphasis is being placed on the evaluation of systems during early stages of the development cycle. The design of systems that include human operators is especially complex because determining overall systems performance is dependent upon the interaction of the human operator, hardware components, and software components (Chubb et al., 1987). Adequately evaluating the performance of a system during the design cycle is becoming increasingly more difficult when using the static evaluation tools traditionally available to the Human Factors engineer, such as job and task analysis (Geer, 1981). It is becoming more common for systems developers to use computer simulation as a design tool instead of hardware models (Gawron and Polito, 1985) and for Human Factors engineers to use computer simulation to enhance the use of static evaluation tools. This is because more sophisticated analysis tools are needed that will allow a controlled evaluation of the human operator/hardware components/software components interaction (Chubb, et al., 1987).

This paper will cover the various uses of simulation, the elements of the human-telerobot interface, and how simulating the human-telerobot interface on the Space Station will result in a better designed system. Before focusing the discussion specifically to the simulation of the human-telerobot interface, it will be useful to briefly define simulation and to cover the major uses of system simulation—independent of the type of system that is being simulated. There will then be a discussion of the areas of the human-telerobot interface and how simulation can contribute to a better designed user interface from a Human Factors perspective.

USES OF SIMULATION

Simulation is the process of imitating or duplicating the actions or processes of some system in a controlled environment (Arya, 1985). Emphasis should be placed on the word "controlled." System simulation, either hardware, computer, or a combination of the two, has been used for decades. This paper will describe four major uses of simulation. One use of simulation is to study the effectiveness of various hardware/software components on overall system's performance. The advantages of using simulation within this context are *cost* — it is cheaper to simulate a system than it is to build one; *time* — simulating a system is usually faster than building it; *feasibility* — because of the size and complexity of some systems, it is not possible to evaluate them in the real world, therefore, simulation serves the function of systems verification; *safety* — some systems operate in dangerous environments and can only be evaluated safely with the use of simulation; and *prediction* — with the use of simulation, a system's performance and processes can be speeded up so that future behavior can be predicted (Arya, 1985).

A second use of simulation is to study the effects of various hardware/software components on simulated human performance. This approach utilizes mathematical models of human performance to assist the simulation process. In this, as well as, the approach mentioned above, man-in-the-loop is not a part of the evaluation.

A third use of simulation is to study the effects of various hardware/software components on actual human performance. This approach can be taken in an attempt to match systems components and operator capabilities and limitations in order to ensure optimal systems and operator performance. This approach can be taken in an attempt to add greater fidelity, and thus, external validity to the data that are gathered in the analysis.

The last use of simulation to be addressed in this paper is to train operators to eventually use a real-world system. The major benefits of simulation as a training aid are in the areas of *scheduling* — training is not affected by weather or the need to perform operational missions; *cost* — simulator training is significantly less expensive than prime system training; *safety* — reduces the exposure of operators and the prime system to the hazards of the operating environment; *control of training conditions* — control of environmental and human interaction conditions that may be a part of the operating environment; *learning enhancement* — system malfunctions and environmental conditions can be included in the training; and *performance enhancement* — inclusion of critical missions that are difficult to train for in the real world (Flexman and Stark, 1987).

As the above list indicates, simulation has significant usage as an aid in the development of pre-existent systems. It can have even greater significance in the design and development of novel pre-existent systems — systems that have never existed before and where few direct comparisons to existent systems can be made. The human-telerobot system that will be used on the Space Station is such a novel system.

Even though industrial robots and teleoperators are heavily used in such areas as the nuclear industry and in underwater activities, there are major differences between these applications and the telerobot system to be used on the Space Station — one of these being the zero-gravity factor. There is also a limited number of direct comparisons which can be made from the Remote Manipulator System (RMS) used on the Space Shuttle and from the proposed telerobot system. The review of the literature concerning these systems has provided answers to some important design issues, but there are major limits to how far these data can be generalized to the human-telerobot interface on the Space Station. Laboratory evaluation of the effects of various hardware and software components on operator performance can, of course, provide answers and guidance, but, perhaps greater fidelity can be attained with the use of simulation.

It is thus proposed that the use of simulation in the design and development of the human-telerobot interface on the Space Station will be very beneficial. Simulation should serve as an aid in the selection and design of hardware and software components to ensure maximum, error-free performance. Simulation should be worthwhile especially for its ability to simulate the effects of zero gravity on performance. Operator performance at manipulation tasks while in a one-gravity environment may well not be generalizable to weightless states. Simulation of the interface should also have the benefit of helping engineers to detect flaws in the design of components of the interface which would adversely affect system and/or operator performance. It is obviously important that any mistakes of this type be detected early and far before the design is finalized or manufacture of the system has occurred.

INFORMATION NEEDS OF THE OPERATOR

There are three broad areas of the human-telerobot interface where simulation can be of assistance: operator information needs, control devices, and workstation layout. These three areas are listed in Table 1. The information needs of the operator will vary depending upon the tasks to be performed. The operator will need information concerning the location and orientation of the telerobot in space, the health status of the telerobot, visual feedback from the viewing system, the status of any transportation devices, the status of the workpiece, and the status of the hardware in the control workstation.

Regarding visual feedback, the visual system may well be the single most important source of information for the operator (Smith and Stuart, 1988). Some of the issues related to the visual system are concerned with camera position and number, the spatial orientation of the image presented to the operator, and monitor type, placement, and number. For example, when performing a remote manipulation task in real time, the operator can view the remote scene either by looking through a window, or with the use of cameras. For most of the tasks that will be performed in space, a direct view of the working area will either not be available, or will not provide the necessary visual cues for teleoperation. Therefore, cameras will provide the primary mode of feedback to the operator concerning manipulator position, orientation, and rate of movement. Operators normally use the body of the manipulator as a reference point when making control inputs, but if the Space Station's external cameras are placed such that the camera view is not normal to the manipulator (normal refers to placement behind the shoulder of the arm), then the visual feedback will be spatially displaced. Spatial displacement is an unfortunate consequence of attempts to provide visual information to the operator when the camera placement is not normal and it should be avoided if at all possible.

TABLE 1.

Three areas of the human-telerobot interface

1. Information needs of the operator
    - Location of telerobot
    - Status of transportation devices
    - Status of workpiece
    - Status of workstation
    - Force feedback
    - Visual feedback
        Camera position and number
        Spatial orientation of image
        Monitor type, placement, number
        Illumination
2. Control devices considered
    - Miniature master controllers
    - 3 or 6 degree-of-freedom hand controllers
    - Exoskeleton controllers
    - Head-slaved controllers
    - Dedicated switches
    - Programmable display pushbuttons
    - Voice command systems
    - Computers
3. Telerobot workstation
    - Hardware layout
    - Software layout

Spatially displaced feedback can take on different forms: *angular displacement,* the reference point is displaced horizontally within the sagittal plane or vertically within the median plane; *reversal* is facing the arm instead of being placed behind it; *inversion-reversal* is upside down and is facing the arm; and *inversion*, the camera is upside down with respect to the manipulator arm. The image can also be displaced *temporally* — there are time delays in which the operator receives the visual feedback, as well as *size distorted* — the image is enlarged or reduced from its actual size. These spatial displacements adversely affect operator performance to varying degrees. Generally, they take on progressively more disturbance with angular displacement being the least disruptive and inversion displacement being the most disruptive. Temporal displacement interrupts the intrinsic temporal patterning of motion and causes severe disruptions in behavior. Much effort should be extended to prevent its occurrence. Size distortions generally do not affect performance to a great extent (Smith and Smith, 1962).

Other visual system issues include how an operator will use multiple views of the task area and how operators can best use non-stereoscopic cues to depth perception. Computer simulation of various task scenarios with human operators working within various hardware and software mockups, including sophisticated scene generation techniques, can serve as an aid in determining what types of information are needed and what types of information presentation enhancements should be used at various points within the sequence of task performance. An example of an information enhancement technique that simulation can investigate is the use of real-time moving graphics displays designed to help operators maintain their orientation while performing under potentially visually disorienting conditions. Other screen-viewing techniques should be investigated with the use of simulation in an attempt to avoid operator disorientation while performing manipulation tasks.

CONTROL DEVICES

Control devices will be used to control such things as telerobot activation, position, manipulators, end effectors, rate of movement, and the viewing system. Control devices being considered include manipulator controllers such as miniature master controllers with direct position control, 3 or 6 degree-of-freedom hand controllers using rate or force inputs, exoskeleton controllers using various position sensors to detect human arm configurations, head-slaved control, dedicated switches, programmable display pushbuttons, voice-commanded systems, and computer displays with cursor-control devices which allow menu selections. Control device selection is important because it affects operator performance, workload, and preference. Computer simulated scenarios could be linked to actual controllers' use to determine their effects on operator performance across different manipulation tasks.

WORKSTATION DESIGN

The telerobot workstation consists of hardware elements, their interfaces, and the software that will allow the hardware to be used. The workstation is the point where the information and control inputs are made available to the operator. Just as with the selection of control devices, the workstation should be logically and functionally laid out to optimize operator performance and preference while minimizing workload and error rates. Again, simulation can help to determine optimal workstation layouts. A simple means of simulating the workstation layout is through the use of computer prototyping, but it is recommended that large-scale simulation be used as a means of designing and evaluating the telerobot workstation.

CONCLUSIONS

Many issues remain unresolved concerning the components of the human-telerobot interface mentioned above. It is then critical that these components be optimally designed and arranged to ensure, not only that the overall system's goals are met, but that the intended end-user has been optimally accommodated. With sufficient testing and evaluation throughout the development cycle, the selection of the components to use in the final telerobotic system can promote efficient, error-free performance. It is recommended that whole-system simulation with full-scale mockups be used to help design the human-telerobot interface. It is contended that the use of simulation can facilitate this design and evaluation process. The use of simulation can also ensure that the hardware/software components have been selected to best accommodate the astronaut, instead of the astronaut having to make performance accommodations for the hardware/software components that have been selected.

As was mentioned above, there are other advantages to simulating the human-teleoperator interface than simply serving as an aid in the selection and design of hardware/software components so that operator performance is optimized. Systems developers can also use the simulation system to test whether or not hardware components meet overall systems goals, and the simulation system can be used for subsequent training of the astronauts who will use the actual system.

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Ergonomics

An astronaut's applied force is measured to determine human capability to perform tasks in space. The CYBEX dynanometer, which is used to evaluate the skeletal muscle strength, power, and endurance of astronauts and astronaut candidates, is used in the Weightless Environment Training Facility (WETF) to simulate zero-gravity.