Teleoperator Visual System Simulations

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A stereoscopic television system, with a fresnel display, and a monoscopic television system were evaluated for teleoperator application using man-in-the-loop visual and motion simulations. Static simulations were used to investigate camera locations and depth alignment. Dynamic simulations, using both a remote manipulator and a six-degree-of-freedom moving base programed with the teleoperator maneuvering characteristics, provided data on operator performance typical of satellite maintenance and spinning and nutating satellite retrieval tasks. Results presented show that, by using a stereoscopic system, viewing locations are less critical and tasks times are reduced for satellite maintenance tasks that require alignment or dexterity. Stereoscopic television, using a fresnel display technique, was recommended for application as the primary teleoperator visual system.

Introduction

PLANS for extending man's exploration and understanding of space may include the use of remotely controlled teleoperators which, when controlled from a safe, habitable location, have the advantage of using man's decision-making ability when unforeseen conditions arise, while contributing significantly to his safety by permitting him to "stand-off" from any hazardous conditions.

Previous work in this area has been reported in a series on remote manned systems in *Astronautics and Aeronautics* from April to July, 1972.[1-5] The series describes the capabilities and advantages of remote manned systems for applications in exploration and exploitation of air, land, sea, and space.

The teleoperator spacecraft consists of four basic elements: 1) a remotely controlled vehicle to provide maneuvering to and from a satellite work site and required mobility about a satellite; 2) one or more manipulative devices representing man's arms and hands to permit performance of tasks at the work site; 3) a visual system analogous to man's eyes to allow viewing the work site and task activity; and 4) a remote control and display station in a manned spacecraft or on the surface of the Earth from which total mission operations can be manually supervised and controlled. One of the most important of these four elements is the visual system because it is the primary sensor used by the operator to accomplish his tasks. Therefore, a detailed simulation program was undertaken to establish the requirements of the teleoperator visual system.

An investigation of applicable television concepts resulted in seven potential systems: a monoscopic and six stereoscopic.[6] The stereoscopic techniques included polarized, color-separated, helmet-mounted, fresnel, lenticular, and foveal-peripheral systems. Based on operator comfort, system complexity, state-of-the-art considerations, and bench-test evaluations, the fresnel was the preferred system. Hence, simulations were conducted using both monoscopic and stereoscopic-fresnel display television systems.

These two systems were assembled and evaluated using man-in-the-loop simulations consisting of three phases: static, master-slave manipulator, and a six-degree-of-freedom moving base. The static phase investigated camera locations and depth alignment. In the second phase, the two systems were compared on the basis of typical teleoperator maintenance operations, using a task panel and a Control Research Laboratories Model L manipulator arm. In the third phase, Martin Marietta's six-degree-of-freedom moving base, programed with the maneuvering characteristics of the teleoperator, was used with a scaled spinning and nutating satellite to provide data on system performance during a satellite retrieval mission.

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Visual System Description

The visual systems incorporated both monoscopic and stereoscopic television. The monoscopic view was identical to the familiar commercial TV systems, while the stereoscopic view was provided by a fresnel-stereo system.[7] The latter, illustrated in Fig. 1, is a simple, but extremely realistic stereo display concept. Signals from two adjacent TV cameras are fed to two TV monitor faces, one for each stereo image. These images are projected through imaging lenses onto a fresnel screen. The screen acts as a field lens and forms a separate exit pupil for each image. The size and shape of the exit pupil are dependent on the imaging lens selected, and the display-to-viewer distance is bounded by the focal length of the fresnel screen. No glasses or other viewing aids are required and hence, random viewing of peripheral controls and displays is natural and effortless. As the two optical axes cross in the image plane, maximum ease of stereo registration is provided. This system is both simple and compact. The complete system, about the size of a suitcase, consists of two 3-in. TV monitors projected onto a 10-in. fresnel

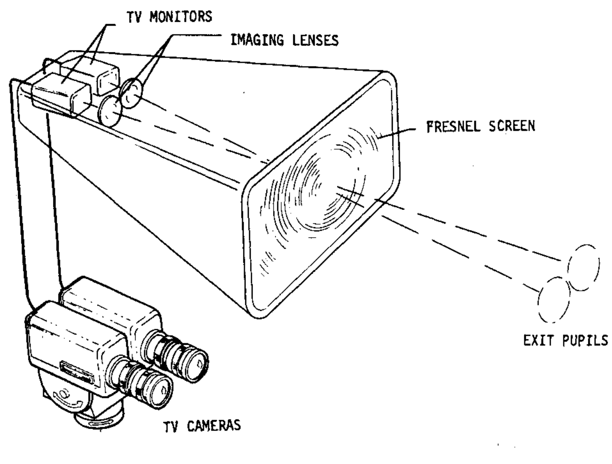

Fig. 1 Stereoscopic fresnel display concept.

display lens. Mirrors provide the required optical path while reducing the over-all display volume.

The two cameras comprising the stereo sensor were separated by a baseline of 4 in. in all of simulations described below. In cases where the object was a scale model, the apparent or simulated camera separation was greater by the inverse of the scale. For example, a task performed with a 4-in. sensor baseline and a $\frac{1}{10}$ scale model simulates a life-size task performed with a sensor baseline of 40 in.

Basic Depth Alignment

The objective of the initial simulation was to provide basic information on the visual systems for general remote viewing. Variables of interest were operator performance and accuracy using monocular and stereoscopic viewing, location of the television camera(s), and the effects of shapes and sizes of objects. The primary task was to align two objects in a common plane.

Apparatus

Experimental hardware consisted of a stand with one degree of freedom, a stationary stand, two television cameras, a standard 10-in. television monitor, the 10-in. fresnel display, and three types of objects (wooden blocks painted flat white used against a black background): two 5 × 2 × 2-in. rectangular solids, one 4 × 1.5 × 1.5-in. rectangular solid, and two 2-in.-diam cylinders, 5 in. long.

Method

The simulation task was to align two objects into the same vertical (Y-Z) plane. One was stationary, while the other could be moved along a horizontal line (X). The objects were maintained 2 in. apart in Y, and the initial location of the movable object was from 4 to 10 in. in front of, or behind, the fixed object. The exact starting distance was random. Once the movable object was started toward the fixed object, it was stopped on command when the subject perceived that the two were aligned in a vertical plane normal to the line of motion (LOM). Alignment error was then recorded.

Numerous tests were conducted in which the independent variables were the shapes and sizes of the blocks, viewing dimension (stereo or mono), and camera location, while the dependent variable was alignment accuracy. The experimental order of the independent variables was counterbalanced across six different subjects.

Results

Alignment errors recorded during the simulation are shown in Table 1. Based on these summary data, conclusions relating to the independent variables were drawn.

Viewing dimension

Stereoscopic viewing proved to be consistently better throughout the simulation tests. This result was anticipated because the task was depth alignment, in which stereoscopic viewing (assuming object size is unknown) is generally recognized as a requirement.

Table 1 Depth alignment—mean positional errors

		Mean errors, in.	
Objects	Camera location	Monoscopic	Stereoscopic
Equal size cylinders	LOM	0.61	0.34
	30° vertical	0.63	0.36
	30° horizontal	1.25	0.72
Equal size blocks	LOM	0.72	0.38
	30° vertical	0.33	0.33
	30° horizontal	1.34	0.63
Unequal size blocks	LOM	2.52	0.55
	30° vertical	...	...
	30° horizontal	...	...

Viewing angles

The simulations indicated little difference between alignment accuracy using a stereoscopic view along the LOM compared with a 30° vertical offset. However, a 30° horizontal offset increased alignment errors by a factor of two.

There was greater difference in using different viewing angles with the monoscopic display. Monocular viewing proved best at a 30° vertical offset because the only cues in monocular viewing are size at the LOM camera position, horizontal position at 30° left, and both size and vertical position at 30° up.

Object shape and size

There was very little difference in accuracy for viewing rectangles and cylinders. However, the test subjects felt that rectangles were easier to align because of their predominant edge cues.

When using rectangles of unequal size, where relative size could not be used as the primary cue, stereo viewing proved significantly better—the errors were less than one-fourth those of monocular errors. For stereo viewing, alignment of equal rectangles was more accurate than aligning the unequal.

When using monocular TV and objects of unequal size, test subjects commented that they could only guess where alignment occurred because they had no feel for it. Alignment errors with monocular TV covered the total possible range, whereas stereo viewing of unequal-size objects produced only a slight decrease in accuracy.

Remote Manipulation

Results of the basic simulation indicated the potential benefits of using stereoscopic TV and the proper viewing angles. However, several questions still remained unanswered. Is stereo viewing as good as having two monoscopic views? Can you generalize the results of simple alignment in one degree of freedom (DOF) to a six- or seven-DOF manipulative task?

Therefore, a simulation was conducted to evaluate two manipulative tasks representative of teleoperator maintenance tasks. The major objectives were to determine if stereoscopic viewing was as good as two monocular views and to determine the effects of camera location and lighting on task performance. Dependent variables were task time and operator preference; independent variables were the viewing dimension (3D and 2D), camera locations, number of views, and light locations.

Apparatus

The manipulator arm used in the simulation analysis was a Central Research Laboratories (CRL) Model L arm with a general-purpose alligator jaw-type end-effector. This arm (Fig. 2)

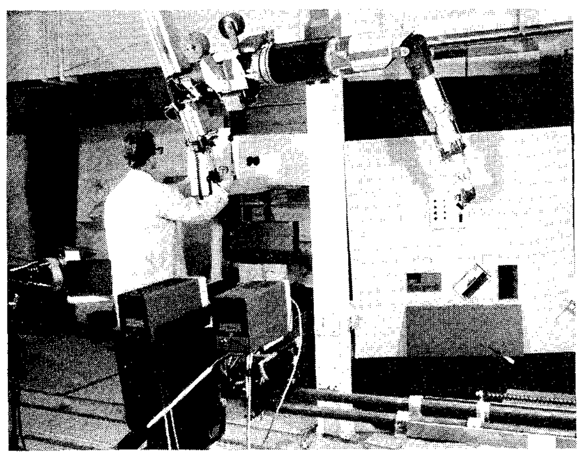

Fig. 2 Manipulator task simulation.

is a master/slave bilateral mechanical manipulator with a reach of about 5 ft. A screen was placed between the master and slave so the operator could use only the video displays to perform the task.

A task panel was constructed that provided two manipulative tasks. The first was inserting a wooden block (0.75 × 1.75 × 9-in.) sequentially into holes $\frac{1}{16}$-in. larger than the blocks. The three holes were oriented at 0°, 45°, and 90° to the horizontal. The second task consisted of inserting a metal drawer into $\frac{3}{16}$-in. larger metal guides offset at 0°, 45°, and 90° from the horizontal.

The displays were the monoscopic and stereoscopic systems previously described. However, two monoscopic displays were provided.

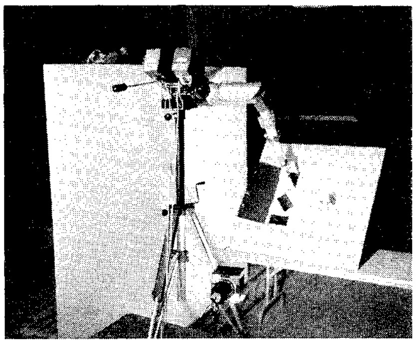

Fig. 3 LOM 45 manipulator simulation setup.

Method

Four experienced CRL arm operators were used as subjects. These operators normally use the CRL arms in Martin Marietta's Environmental Effects Lab. from 3 to 8 hr each day.

To minimize learning effects and establish camera, task panel, and lighting locations for the simulation tests, several pilot studies were conducted while training the operators. Approximately 20 one-view and two-view methods were investigated using four primary evaluation setups. For the "45 right" setup, the task panel was vertical and the cameras offset 45° horizontally. For the 45/45, the task panel was 45° to the vertical, while the camera was horizontally offset 45°. The horizontal LOM had the cameras perpendicular to the panel. In the LOM 45 setup, both the task panel and cameras were offset 45° to the vertical as shown in Fig. 3.

The task was begun by grasping the block in the hole on the right. The operator removed the block and inserted it, first into the left hole, then into the middle hole, and finally into the right hole, leaving it there. He then grasped the drawer in the top guide, removed it, and placed it successively in the bottom, middle, and top guide. Total time required to perform the task was recorded.

Results

The results are based on operator preference, comments, and forced-choice rankings. The task was highly repetitive, requiring the same operations. The operators would learn the task so they could eventually perform it with much degraded visual cues using kinesthetic feedback. Therefore, task times were somewhat misleading, and subjective comments were more reliable indicators of task difficulty.

Viewing dimension

It was generally concluded that stereoscopic was better than monoscopic viewing for all camera locations. In fact, one stereo view was preferred over two mono views. Tasks that required the operator to align in pitch and yaw were impossible using the one-view mono unless the camera's line-of-sight (LOS) was normal to the pitch and yaw axes. This was not always possible because of the manipulator arm or other objects obstructing the camera's view. Therefore, it was concluded that at least two mono views are required for an operational system. However, one-view stereo is sufficient, even for these off-axis alignments.

Camera location

For any manipulator arm configuration it is assumed that the control system will allow control in monitor axes. That is, an up and down motion of the controller moves the slave up and down in the monitor, left and right movements of the controller are left and right in the monitor; and in and out controller motions are in and out in the monitor. In an actual teleoperator system with a manipulator arm, the relationship of the master arm to the monitor, and that of the camera to the slave arm, should be identical.

The next most important considerations of camera location is its relationship to the principal axes of the task panel. The optimum view of an alignment task is, of course, with an LOS perpendicular to the axis of alignment. Therefore, for a task with a close tolerance for alignment in the horizontal (Y) axis, one would want the camera's LOS perpendicular to the Y axis of the task. But, since the simulation task panel was constructed for equal tolerances in both the Y and Z (vertical) axes, the operator required equal information on Y and Z alignment errors, but little information on X errors (normal to the face of the panel). Therefore, optimum viewing for Y and Z would be with the camera's LOS parallel to the X axis, which would require estimating depth or size for X-axis alignment.

The preferred location for one-view stereo was 45° to the right because of viewing interference problems with the arm, shadows, and glare when the camera was pointed along the LOM. However, the required camera location for one-view monoscopic control was in the LOM because of the serious angle-estimation problems associated with the 45° location.

Lighting

Lighting proved to be a much more important variable than was anticipated. High-contrast ratios, such as those found in space flight, mean that shadows or glare will entirely obscure the view of certain areas.

For the simulation, one light was used at a time to independently evaluate each lighting position. However, it is felt that multiple light sources should be evaluated because of several problems encountered with single light sources. For example, to minimize shadow effects in a one-light system, it was evident that the light should be on or near the camera. In this way, any object that casts a shadow also blocks the camera's view of the area under the shadow. However, this arrangement could not be used when the cameras were mounted in the LOM or two-camera 45 left and 45 right locations.

In the former case, intense glare from the face of the task panel reflected into the camera. Positioning the light 10° to the left not only eliminated glare, but also minimized shadows for manipulating blocks on the right side of the task panel. In contrast, since the drawers were much larger, their alignment was not significantly affected by small shadows and lighting position was less critical.

For the two cameras that were both 45° to the panel, the light could not be placed on either camera because of reflections from the task panel and into the other camera. Hence, the obvious recommendation is not to have two cameras in the same plane with equal incidence angles to a reflective surface.

Experiment results indicate that lighting location is critical. For example, on two occasions with the horizontal LOM cameras, moving the light source only 15° reduced task time more than 50%. In several instances, for a one-view stereo visual system, shadow-filling lights were as beneficial as a second monocular view.

Satellite Retrieval

The objective of the third simulation was to investigate remote viewing requirements associated with retrieving a spinning and nutating satellite, using a retrieval manipulator attached to a teleoperator spacecraft.

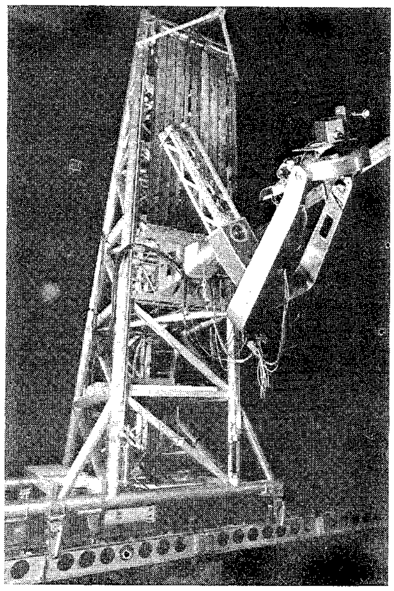

Fig. 4 Space operations simulator.

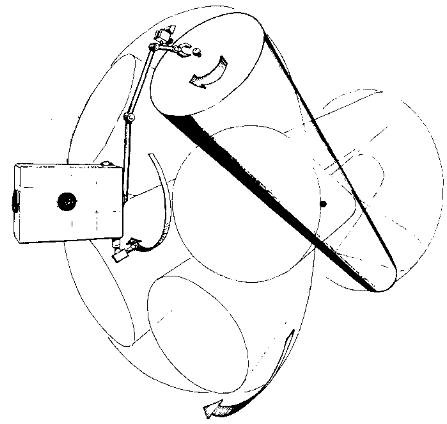

Fig. 6 Satellite retrieval concept.

Apparatus

The simulation used Martin Marietta's Space Operations Simulator (Fig. 4)—a six-degree-of-freedom, servodriven, computer-controlled device that uses a gimbaled attitude head to produce three rotational degrees of freedom and a moving base to produce three translational degrees of freedom.

Teleoperator and retrieval manipulator dynamics were mathematically modeled and appropriately scaled on an EAI 231-R analog computer. The resultant analog signals were applied to the moving base and attitude head of the simulator.

The spinning and nutating satellite was simulated by using a $\frac{1}{20}$ scale model of a 15-ft-diam 60-ft long cylindrical satellite attached to a spin motor (Fig. 5). The combination of the model and spin motor was then attached to a two-degree-of-freedom servodriven gimbal whose spin and gimbal rates were controlled by the analog computer. This configuration was capable of simulating satellite spin rates from 0 to 100 rpm and nutation rates from 0 to 10 rpm.

The control station contained the teleoperator translational and rotational rate controllers, a pencil controller for manipulator length, and a potentiometer for manipulator rotational rate. An oscilloscope displayed a rotating pip and indicated the angular position of the retrieval manipulator with respect to the teleoperator spacecraft control axes. Visual displays were either monoscopic or stereoscopic television.

Method

The basic method used in the satellite retrieval simulation was proposed by NASA (MSFC) personnel.[8] The approach (Fig. 6) consists of initially aligning the teleoperator spacecraft with the satellite nutation axis, extending the retrieval manipulator to the required length, and rotating it to match the nutation rate of the satellite. When the manipulator arm is accurately tracking the satellite capture point, attachment is made, and the satellite is denutated and despun with the manipulator.

However, to perform this task, the remote operator must be able to align the spin axis of the manipulator arm with the nutation axis of the satellite and estimate the satellite's nutation angle and rate in order to establish the required length and rate of rotation of the manipulator. Therefore, the satellite retrieval simulation was divided into two phases. The first used a camera fixed to the teleoperator to estimate the nutation angle and rate and to establish spacecraft alignment with the nutation axis of the satellite. The second phase was to extend and spin up the manipulator arm to match the estimated nutation angle and rate. Then, using a camera on the end of a manipulator arm, a final tracking of the satellite spin axis was performed.

Phase I: Initial alignment

The operator's task was to estimate the nutation angle of the satellite from two positions relative to the satellite—parallel and perpendicular to the nutation axis. After the test subject had estimated the nutation angle, he was instructed to align the attitude and position of the teleoperator camera axis with the nutation axis of the satellite. When the operator felt he was positioned on the nutation axis, his final conditions were recorded.

Independent variables of interest were the initial location of the teleoperator (about 100 ft to the side or in front of the satellite), the satellite nutation rate (0.5 or 10 rpm), the satellite spin rate (0, 50, or 100 rpm), the satellite nutation angle (0–30°),

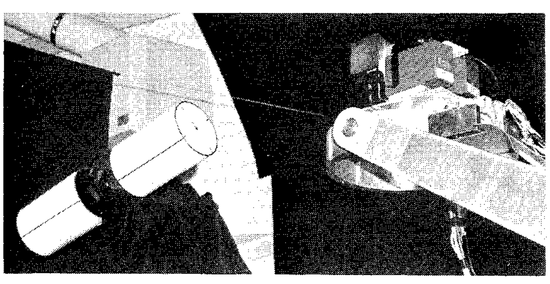

Fig. 5 Spinning/nutating satellite model.

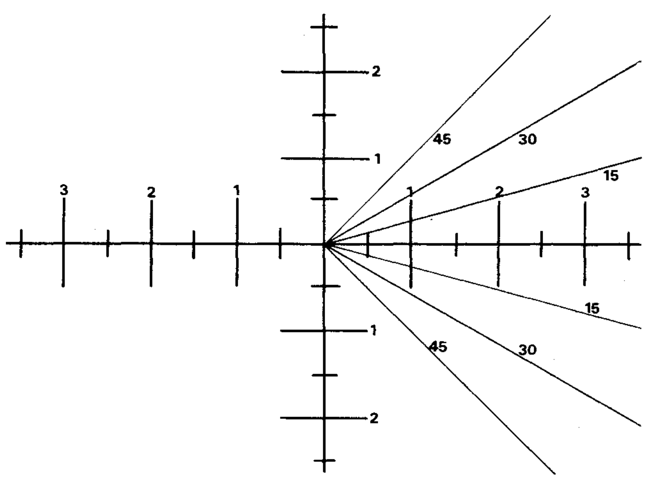

Fig. 7 Reticle overlay.

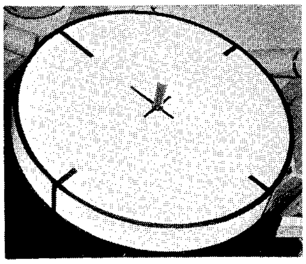

Fig. 8 ¼ scale satellite model.

and the viewing dimension (monoscopic or stereoscopic). Dependent variables were the operator's estimate of the nutation angle, his alignment perpendicular to and parallel to the axis of nutation, and the time required to complete the task. A reticle (Fig. 7) was overlayed on the monoscopic display screen during this phase. The reticle for the stereoscopic display was simply a series of horizontal lines 1-in. apart. The reticles were compared by using the stereo reticle on the monoscopic display.

Phase II: Final alignment

In Phase II, the operator's task was to extend and rotate the retrieval manipulator, based on the requirements estimated from the Phase I results. Subsequently, all Phase I estimation errors had to be detected and corrected until the satellite capture point was accurately tracked. To increase the simulation scale during this task, the satellite was replaced by a ¼-scale model of the circular face of the cylindrical satellite (Fig. 8). This model was rotated at the satellite spin rate, but the visual motion resulting from nutational estimation errors was provided by the moving base simulator. The display presented a view from cameras attached to the end of the retrieval manipulator.

Sources of error the operator had to detect and correct included the length or extension of the manipulator, its rotational rate, and teleoperator attitude and positional errors with respect to the satellite nutational axis. For example, if the manipulator was too short, the satellite would be constantly displaced above the center of the display field of view; if rotating too slow, the satellite appeared to drift to the operator's left; positional errors in the vertical (Z) or horizontal (Y) axes resulted in a circular motion of the satellite on the display, while teleoperator spacecraft yaw and pitch errors appeared primarily as in-out satellite motion. By knowing the relative location of the manipulator with respect to the teleoperator, via the rotating pip oscilloscope display, the test subject was provided with visual indications of the proper teleoperator corrective commands.

Upon completion of Phase II, basically to null all relative rates and center the satellite capture point on the display screen, the simulation was terminated and the operator's final alignment conditions and total task time were recorded.

Results

The results of the satellite retrieval simulation, for both the initial and final alignment phases, are shown in Table 2.

Nutation angle estimation

Test subjects could determine nutation angles under 30° to less than 4° when viewing the satellite from the side, but to only 16° when viewing the satellite from the cylindrical end.

Spin nutation rate estimation

Results show that by using only a stopwatch, spin rates up to 100 rpm and nutation rates up to 10 rpm were easily and accurately determined by all test subjects. In an actual operation, the operator should count the number of revolutions at least twice, as a precaution, because on one occasion a test subject miscounted.

Viewing dimension

Test subjects preferred the monocular view. This was primarily a result of better resolution, head-movement freedom, and a lower operator fatigue factor over that provided by the stereoscopic display. However, as indicated by the alignment accuracies, stereo was the more accurate and recent improvements in the stereo system,[9] when tested, may alter the subjects' viewing preference.

Conclusions

Stereoscopic television permits adequate alignment of different size objects from any of the three viewing angles. However, locating the cameras 30° up produced the best results. Monoscopic television is adequate for alignment of equal size objects. For unequal size objects, alignment is not possible unless more than one view is provided or the camera is located normal to the LOM required for alignment.

For manipulative tasks requiring dexterity and six-degree-of-freedom alignment, a two-view monoscopic system and a one-view stereoscopic system are approximately equivalent. The stereoscopic camera location is not as critical as those required by the monoscopic system, resulting in a less complex teleoperator spacecraft camera deployment system.

The satellite retrieval task demonstrated the need for visual aids. The television cues were not sufficient and the task was difficult without the rotating pip indicating the position of the

Table 2 Satellite retrieval—mean alignment errors

	Nutation angle deg (SD)[a]		Teleoperator attitude deg (SD)		Teleoperator translation ft (SD)	
Viewing locations	Mono	Stereo	Mono	Stereo	Mono	Stereo
Phase I						
Perpendicular to nutation axis at 100-ft range	0.7 (0.7) 0.0 (2.7)[b]	−0.3 (2.5)	−6.5 (3.2)	−10.1 (5.0)	...	...
Parallel to nutation axis at 100-ft range	−5.1 (0.3) −4.1 (6.6)[b]	−0.2 (2.6)	2.6 (0.9)	1.6 (0.6)	3.9 (3.0)	2.8 (1.6)
Phase II						
Parallel to nutation axis at 15-ft range	...	...	1.2 (1.0)	1.2 (0.8)	0.16 (0.10)	0.14 (0.06)

[a] Standard deviation.
[b] Monocular reticle.

manipulator arm relative to the teleoperator spacecraft control axes.

A stereoscopic television system with a fresnel display is recommended for application on teleoperator spacecraft. However, the visual system is strongly influenced by the specific tasks and manipulator complexity required of the teleoperator and should be evaluated in the future as these are identified in adequate detail.

Further study of teleoperator visual systems is recommended to provide additional data in the areas of lighting, display improvements, stereoscopic reticles, and additional visual aids.

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