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THE EFFECTS OF SPATIALLY DISPLACED VISUAL FEEDBACK ON REMOTE MANIPULATOR PERFORMANCE

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INTRODUCTION

Telerobotics will be heavily used for the assembly, maintenance, and servicing of NASA's Space Station *Freedom*. The visual system may well be the single most important source of information for the operator of the various telerobot systems that will be used. When performing a remote manipulation task, 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 on the Space Station, a direct view of the work 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 with respect to the manipulator (normal refers to placement approximately behind the shoulder of the manipulator arm) then the visual feedback will be spatially displaced. At a fundamental level, displacement refers to there not being a one-to-one spatial correspondence between control inputs and perceived motion (either directly perceived through a window view or perceived on monitors). 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. If displaced visual feedback is presented to the operator, system performance can be seriously degraded due to operator disorientation. This is important for Space Station *Freedom* telerobotic tasks because it is possible that cameras may be placed on Station structure such that the human operator receives displaced visual feedback.

If control inputs are referenced to the body of the manipulator (analogous to the "world" mode in industrial robotics) the following descriptions can be made. Spatially displaced feedback can take on four different forms: *angular displacement,* where the reference point is displaced horizontally or vertically (see Figure 1 for a depiction of horizontally displaced angular feedback and Figure 2 for vertically displaced angular feedback); *reversal displacement*, where the camera is facing the arm instead of being placed behind it (see Figure 3 for a depiction of reversal); *inversion-reversal displacement*, where the camera is upside down and is facing the arm (see Figure 3); and *inversion displacement*, where the camera is upside down with respect to the manipulator arm (see Figure 3).

It has been suggested that these spatial displacements adversely affect operator performance to varying degrees. The literature states that direct manipulation tasks take on progressively more disturbance, with angular displacement being the least disruptive and inversion displacement being the most disruptive (Smith and Smith, 1962). Direct manipulation is where a person manipulates an object with their bare hands or with a simple, rigid tool such as a stylus or screwdriver. A remote manipulation task is where the person manipulates a mechanism (e.g., hand controller) which transfers the operator's motions to a remotely placed mechanical device. The actual manipulation of the object is spatially removed or distant from the operator.

Early studies on spatial displacement were conducted by Helmholtz, Kohler, Smith and

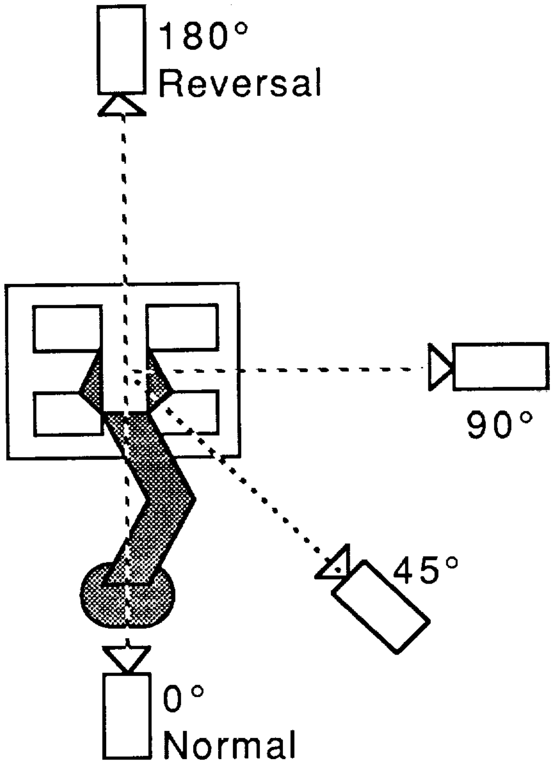

Figure 1. Angularly displaced feedback, horizontally displaced about the manipulator (top view shown).

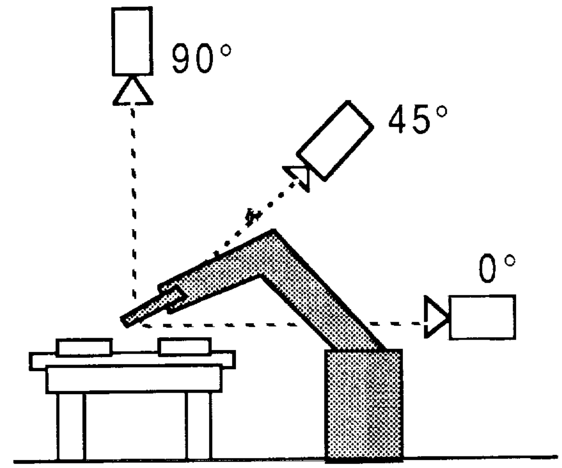

Figure 2. Angularly displaced feedback, vertically displaced about the manipulator (side view shown).

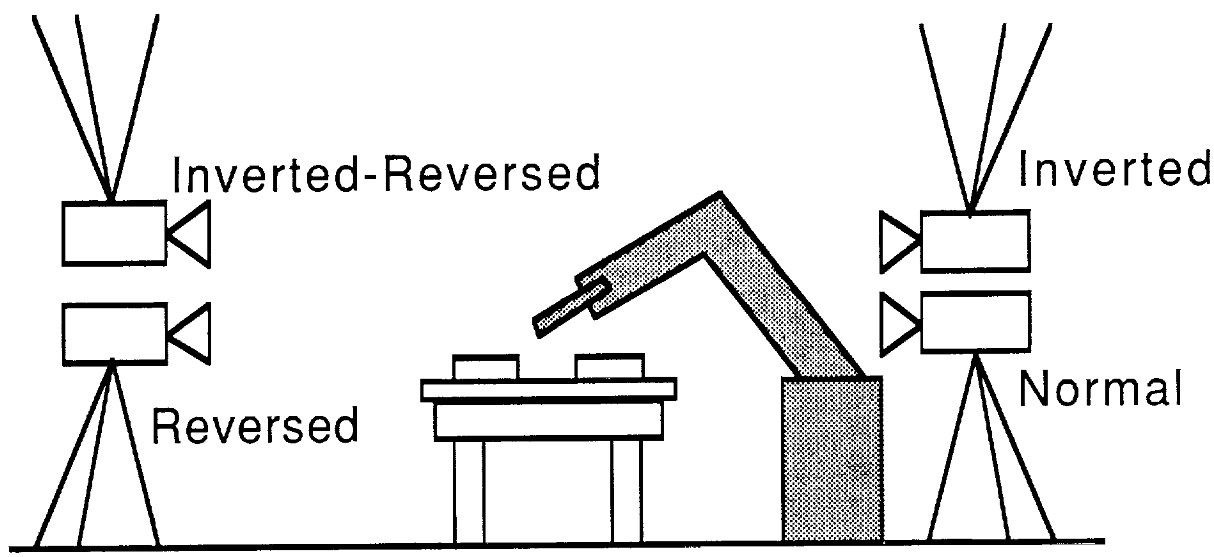

Figure 3. Spatially displaced feedback -- normal, reversal, inversion, and inversion-reversal (side-view shown).

Smith, et al. Smith and Smith (1962) were interested in perceptual-motor integration, specifically the effects of spatial and temporal displacements of the visual feedback of motion. According to Smith and Smith (1987) their work was incorporated into the neurogeometric organization of behavior in which "space perception and visually controlled movement are learned, the nature and degree of learning are determined by the nature and degree of spatial compliance between muscular control and sensory input." There have been numerous studies of viewing systems for telerobotic systems; however, it is difficult to draw coherent and generalized conclusions from them (Crooks, Freedman, and Coan, 1975; Horst, Rau, LeCocq, and Silverman, 1983; Chu and Crooks, 1980; Clarke, Hamel, and Draper, 1983; Bodey and Cepolina, 1973; Huggins, Malone, and Shields, 1973; Onega and Clingman, 1973; Fornoff and Thornton, 1973; and Clarke, Handel, and Garin, 1982).

OBJECTIVES

One objective of this investigation was to quantify whether the above mentioned results from the literature hold true for remote manipulation tasks performed with a remote manipulator arm. It was also of interest to informally evaluate how a direct view of the worksite compares to a normal camera-aided view of the worksite. This secondary evaluation was an attempt to determine if the results obtained in a previous evaluation (Smith, 1986) of remote manipulator operators, who had both direct and normal camera views, could be replicated. The present investigation examined operators performing a remote manipulation task while exposed to the following different viewing conditions:

- direct view of the work site (baseline condition)
- normal camera view (zero-degree displacement)
- reversed camera view (180-degree displacement)
- inverted/reversed camera view
- inverted camera view

METHOD

Data were collected from subjects as they performed a remote manipulation task while exposed to the different viewing conditions. All six subjects used the five viewing conditions.

SUBJECTS

Six volunteer subjects were used in this evaluation. All were experienced in the operation of the Kraft robotic system.

APPARATUS

Testing took place in the Man-Systems Telerobotics Laboratory at NASA's Johnson Space Center (JSC).

A Kraft Telerobotics force-reflecting 6 degree-of-freedom master-slave remote manipulator was used to perform the remote manipulation task. A Javelin CCD color camera and a Mitsubishi 20-inch color video monitor were used to present the camera views to the subjects. The camera in each position was exactly 10 feet 2 inches from the remote manipulation task, with the focus and zoom controlled. The direct view was from a distance that was controlled so that the visual angle subtended at the eye by the task piece was approximately the same for both camera and direct views.

The task consisted of grasping and moving six pyramid-shaped wooden blocks so that they could be dropped inside a metal box located six inches from the blocks on the taskboard. This particular task was selected because it is functionally similar to multi-axis translation and alignment tasks which will be performed by the telerobots on Space Station *Freedom*.

Each subject sat behind a barrier for the camera-aided viewing conditions so that a direct view of the worksite was not possible. For the direct viewing condition, the subjects faced the Kraft manipulator arm with a zero-degree displacement view.

VARIABLES

The independent variable in this study was the different camera viewing conditions (normal, image reversal, image inversion/reversal, and image inversion). Note that the noncamera viewing condition (direct view) was not an independent variable, but was only used as a baseline measure. This evaluation used a one-factor repeated measures design — all subjects were exposed to all levels of the independent variable used. The dependent variable in this evaluation was task performance time.

PROCEDURES

Subjects were instructed to perform the remote manipulation task quickly and accurately. All subjects performed the manipulation task with the direct view first. This served as the baseline condition by which the performance times for all the other viewing conditions could be compared. Each subject then performed the manipulation task for each of the four different camera-viewing conditions. Each subject performed the task a total of five times. The order in which subjects were exposed to the four different camera views was counterbalanced to control for order effects. Task performance times were collected throughout the test sessions.

RESULTS AND DISCUSSION

The task completion time data were collected and summarized. The average performance times (in minutes) are summarized as follows:

Direct (baseline)	0.59
Normal	1.20
Inverse/Reverse	5.00
Reverse	6.02
Inverse	9.51

The task completion times were then statistically analyzed with a repeated measures analysis of variance. It was determined from the ANOVA that the main effect of the viewing conditions, $F(3,15) = 7.72$, $p < 0.05$, was statistically significant. Because of this result, a Newman-Keuls pairwise comparison test was then administered to the data. It was revealed that the performance times for the inverted camera view were significantly ($p < 0.05$) worse than all of the other viewing conditions. This analysis also revealed that the reversed viewing condition was significantly worse than the normal viewing condition. The performance times for the inverted camera viewing condition were also significantly worse than the normal viewing condition performance times at $p < 0.01$.

It was also of interest to compare the performance of subjects under the direct-viewing condition to the performance of subjects under the normal camera-viewing condition. It was hoped that a statistically valid comparison could be made between these two viewing conditions, but since all subjects performed the direct-viewing condition first and the normal-viewing condition either second, third, fourth, or fifth out of all viewing conditions used in this study, then the results for this analysis could well be contaminated by the effect of differential amounts of training. A valid statistical comparison could not be made between these two viewing conditions because the experimental design in this study was used to counterbalance four different viewing conditions, not two. An informal comparison was made for the sake of general interest. This informal comparison involved partitioning the normal viewing-condition data from the rest of the camera-viewing data. These data and the direct-viewing data were analyzed with a *t*-test. This data analysis revealed that the task performance times for the normal viewing condition were significantly slower ($p < 0.05$) than for the direct viewing condition. It is recommended that further studies conduct an analysis of these two viewing conditions under proper experimental conditions so that an accurate assessment can be attained.

It is clear from the results of this study that spatially displaced visual feedback adversely affects remote manipulation performance. To get an indication of how views of the remote manipulator through a CRT monitor change with respect to hand controller movements for the four types of visual feedback studied in this

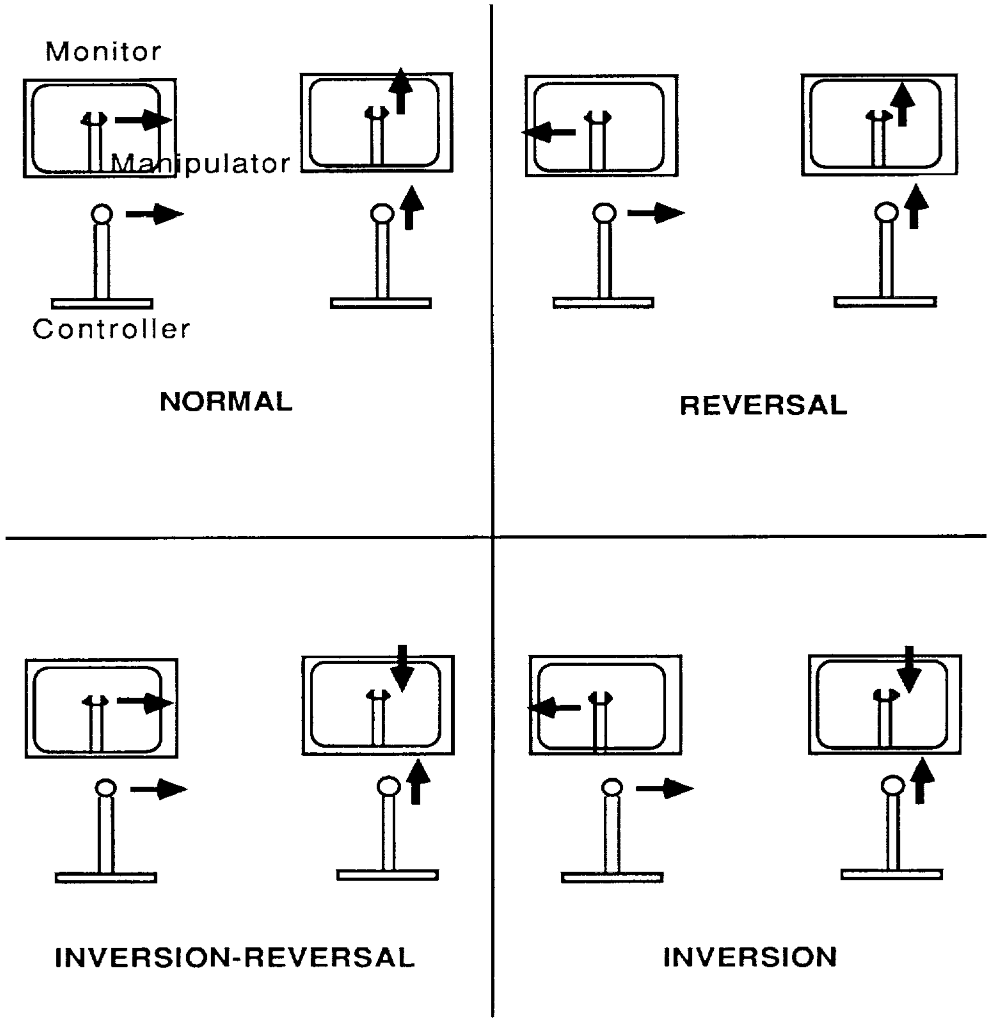

Figure 4. Viewed manipulator movements with respect to controller movements for four types of visual feedback.

evaluation, refer to Figure 4. In this figure, the object in the monitor is the remote manipulator. The arrows indicate the direction that the manipulator will move in the video image with respect to the specific hand controller movement for the four different camera placements. For example, in the inverted visual feedback condition, a rightward movement of the hand controller will result in the monitor image of the manipulator moving leftward and an upward hand controller movement will result in the monitor image of the manipulator moving downward.

The results obtained were not quite as would be expected based upon the previously mentioned studies of camera-aided viewing of direct manipulation tasks. The difference observed in this evaluation was that, in ranking the four viewing conditions, the reversed camera view was ranked third while the literature stated that the inversion/reversal was third. The reversed-viewing condition not only took over a minute longer, on the average, to complete than the inversed/reversed condition, but it was also significantly worse than the normal viewing condition performance time. The differences obtained in this evaluation could be due to the fact that the remote manipulation task used in the present study involved the use of axes of movement different from those involved in the direct manipulation tasks reported in the literature. The axis of movement, the quantity of movement per axis, and the type of displacement are interrelated in a fashion that probably affects performance times; however, quantitative determination of these interrelationships is beyond the scope of this preliminary evaluation. The differences obtained could simply be due to the fact that the sited direct manipulation results were based upon data gathered from many different studies while the remote manipulation data came from only one study. More remote manipulation studies will need to be conducted before this conclusion can be made.

This study did informally replicate the results of the previously mentioned study by Smith (1986) which found, among other things, that performance with a normal camera view of the worksite is significantly worse than performance with a direct view. This result is no doubt partially due to the lack of binocular disparity that accompanied the camera viewing conditions.

CONCLUSIONS

The results of this evaluation have important implications for the arrangement of remote manipulation worksites and the design of workstations for telerobot operations. This study clearly illustrates the deleterious effects that can accompany the performance of remote manipulator tasks when viewing conditions are less than optimal. Future evaluations should emphasize telerobot camera locations and the use of image/graphical enhancement techniques in an attempt to lessen the adverse effects of displaced visual feedback. For a further discussion of the effects of perturbed sensory feedback see Smith, Smith, Stuart, Smith and Smith (1989).

An important finding in this evaluation is the extent to which results from previously performed direct manipulation studies can be generalized to remote manipulation studies. Even though the results obtained were very similar to those of the direct manipulation evaluations, there were differences as well. This evaluation has demonstrated that generalizations to remote manipulation applications based upon the results of direct manipulation studies are quite useful, but they should be made cautiously.

ACKNOWLEDGEMENTS

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