EFFECTS OF SPATIALLY DISPLACED FEEDBACK ON REMOTE MANIPULATION TASKS

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ABSTRACT

Several studies have been performed to determine the effects on computer and direct manipulation task performance when viewing conditions are spatially displaced. Whether results from these studies can be directly applied to remote manipulation tasks is questionable. The objective of this evaluation was to determine the effects of reversed, inverted, and inverted/reversed views on remote manipulation task performance using two 3-Degree of Freedom (DOF) hand controllers and a replica position hand controller.

Results showed that trials using the inverted viewing condition showed the worst performance, followed by the inverted/ reversed view and the reversed view when using the 2x3 DOF. However, these differences were not significant. The inverted and inverted/reversed viewing conditions were significantly worse than the normal and reversed viewing conditions when using the Kraft Replica.

A second evaluation was conducted in which additional trials were performed with each viewing condition to determine the long term effects of spatially displaced views on task performance for the hand controllers. Results of the second evaluation indicated that there was more of a difference in performance between the perturbed viewing conditions and the normal viewing condition with the Kraft Replica than with the 2x3 DOF.

INTRODUCTION

Telerobotics will play an essential role in the assembly, operation, and maintenance of NASA's existing and future spacecraft. Direct views of the worksite will not be available or sufficient for many telerobotic tasks, so cameras will provide the primary mode of visual feedback. Due to structural and logistical constraints on Space Station *Freedom*, cameras cannot always be located to provide the optimal view of the task site, and the views presented to the operators will most likely be spatially displaced. Task performance with distorted views may be adversely affected, with some distortions causing more of a decrement than others.

Camera views are generally referenced to the equipment performing the task. During direct manipulation (when tasks are performed using hands or simple tools), a "normal" camera view, with no spatial displacement, is considered to be a view from behind the person's hands. With remote manipulation (in which operations are performed by mechanical devices controlled by a human from a distance), a "normal" view is considered to be from behind the manipulator arm.

Various types of spatial displacements have been classified and examined in relation to task performance. Spatially displaced feedback can take on four different forms: (1) *angular displacement*, in which the reference point of the camera in relation to

the arm is either displaced along the horizontal axis or the vertical axis, (2) *reversed displacement*, in which the camera faces the task board and the arm, (3) *inverted displacement*, in which the camera is behind an upside-down with respect to the manipulator arm, and (4) *inverted-reversed displacement*, in which the camera is upside-down and faces the task board and the manipulator arm. Performance using visual perturbations is usually compared to performance using a direct view or a normal camera view.

Several studies have been performed to determine the effects on computer and direct manipulation task performance when the viewing conditions are spatially displaced (Bernotat, 1970; Kim, Tendick, and Stark, 1987; Smith and Smith, 1962). Whether results from these studies can be directly applied to the remote manipulation tasks to be performed on various space platforms is questionable.

There have been few studies examining the effects of spatially displaced feedback on remote manipulation task performance. A study conducted by Stuart and Smith (1989) investigated the effects of normal, reversed, inverted and inverted/reversed viewing conditions on a remote manipulation task. Their results found that remote manipulation performance using the inverted viewing condition was significantly worse than performance with any of the other views, and that the direct view provided the best performance. A follow-up study showed that all perturbed viewing conditions were significantly worse than the normal view, but none of the perturbed views was significantly better or worse than another (Stuart, Bierschwale, Sampaio and Legendre, 1990).

The two remote manipulation evaluations mentioned above used a replica mini-master position hand controller system. Since these studies were completed, an extensive investigation performed by several laboratories at the Johnson Space Center has shown that task performance with orthogonal rate hand controllers (in particular, with the 2x3 DOF type hand controllers) is significantly enhanced when compared to task performance with replica mini-master hand controllers (NASA/MSD, 1991). Based on the results of this study, the baseline hand controller for Space Station Freedom was deemed to have a 2x3 DOF rate configuration. In light of these results, it was considered imperative to incorporate the orthogonal baseline configuration into current investigations of perturbed visual feedback on remote manipulation task performance.

This experiment augmented the previously mentioned perturbed feedback remote manipulation evaluations, to include the 2x3 DOF hand controller configuration. It was hypothesized that performance using perturbed viewing conditions would vary between the orthogonal and the replica hand controller, and that strategies for task performance may also differ. The objectives of this evaluation were as follows:

1. Determine the effects of reversed, inverted, and inverted/reversed views on remote manipulation task performance with a 2x3 DOF hand controller.

2. Compare the effects of spatially displaced views on remote manipulation with a 2x3 DOF hand controller and the Kraft Replica hand controller.

METHOD

The primary objectives of this evaluation consisted of determining the effects of spatially displaced views on task performance with the 2x3 DOF and comparing it to the Kraft Replica.

Subjects

The four test subjects from the previous study (Stuart, Bierschwale, Sampaio, and Legendre, 1990) also participated in this study so that a valid comparison could be made. All test subjects were experienced in performing remote manipulation tasks and with both hand controllers used.

Apparatus

Testing was conducted in the Remote Operator Interaction Laboratory (ROIL) at NASA's Johnson Space Center.

A Honeywell Apollo modified 2x3 DOF, orthogonal, rate mode hand controller and a Kraft Telerobotics force-reflecting, replica, mini-master hand controller were used to operate a Kraft Telerobotics 6 DOF remote manipulator to perform the task. A single closed circuit color camera and a 19" color monitor were used to provide the camera view at the subject's workstation.

Variables

The independent variables in this evaluation were the hand controllers (Honeywell 2x3 DOF and Kraft Replica), viewing conditions (normal, reversed, inverted, and inverted/reversed), trials (three), and subtasks (four). This evaluation used a nested repeated measures design; all subjects were exposed to all levels of the independent variables used. However, each hand controller's data were analyzed separately due to operational differences.

The dependent variables in this evaluation were trial completion time, subtask completion time, number of errors, and subjective questionnaire responses.

Procedure

Test subjects were given an overview of the remote operation and instructed to complete the task as quickly and accurately as possible. No information on camera position was given.

The task performed in this investigation was functionally similar to multi-axis translation and alignment tasks which will be performed by the telerobots on space platforms. Three trials of the task were performed with each viewing condition, and the task consisted of four subtasks.

To familiarize test subjects with the task, three trials of the remote operation were first performed with the direct view, in which no camera view was provided. During this time, the test administrator coached subjects on general techniques to avoid manipulator joint limits by using cues on the manipulator and keeping the end effector within a defined work zone. After completion of three trials using the direct view, three trials were performed with each of the four camera viewing conditions in counterbalanced order. Hand controller order was also counterbalanced.

RESULTS

Performance and subjective measures were analyzed using the Clear Lake Research Analysis of Variance (CLR ANOVA) statistics program and Duncan's multiple range test.

ANOVAs were used to analyze the following variables: task completion times across all trials (i.e., if one viewing condition was significantly longer than another for all three trials), task completion times within each trial (i.e., if one viewing condition was significantly faster than another during any one of the three trials), and completion time within each subtask (i.e., if the any of the viewing conditions were significantly different from another viewing condition during any of the four subtasks). Separate ANOVAs were performed on data collected from the 2x3 DOF and the Kraft Replica hand controllers. Results from analyses performed on subtask completion times and errors were complementary to the other analyses, and thus will not be presented for the sake of brevity. Only significant results will be presented in the sections below.

Completion Times for 2x3 DOF Hand Controller

Marginally significant differences (p=.0711) were found during the analysis of the viewing condition completion time data. Figure 1 shows the completion times for the trials with each viewing condition. Note that trials using the inverted viewing condition were longer than trials using any of the other three viewing conditions. The completion time for the three trials was significantly different (p<.05), with the Duncan's paired-comparison test revealing that task completion time for trial 1 was significantly longer than completion time for trials 2 and 3.

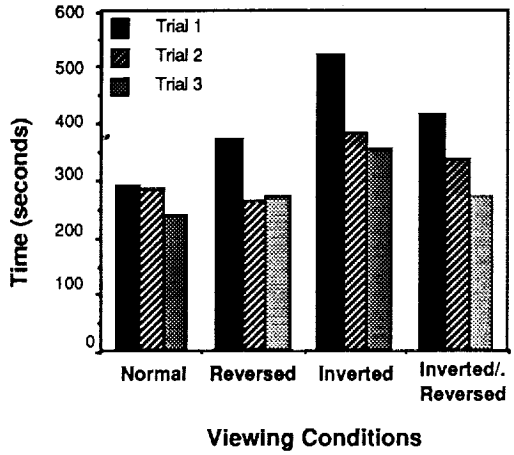

Figure 1. Completion Times for 2x3 DOF Hand Controller

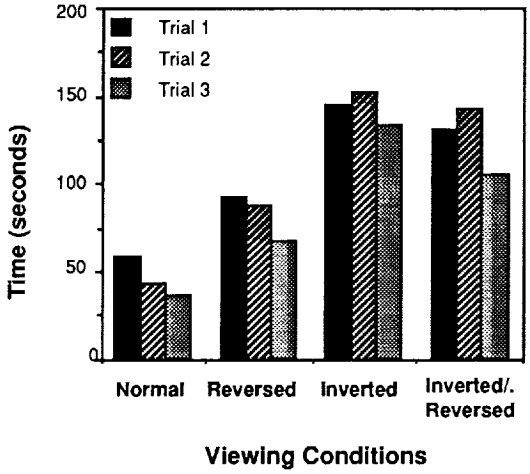

Figure 2. Completion Times for Kraft Replica Hand Controller

The ANOVA performed within each of the three trials showed that the viewing conditions were significantly different only during trial 3 ($p<.05$). The Duncan's test revealed that the inverted viewing condition was significantly slower than the other three viewing conditions.

Completion Times for Kraft Replica Hand Controller

There was a significant difference among the four viewing conditions ($p<.01$). The Duncan's pairwise comparison test indicated that the normal and reverse viewing conditions were both significantly quicker than the inverted and inverted/reversed viewing conditions. Figure 2 shows the completion times for each of the viewing conditions and trials.

An ANOVA performed within each trial showed that the viewing conditions were significantly different within each of the three trials ($p=<.05$ for trial 1, $p<.05$ for trial 2, and $p<.05$ for trial 3). Duncan's tests indicated that the normal viewing condition was significantly faster than the inverted and inverted/reversed viewing conditions during all three trials and that the reversed viewing condition was significantly faster than the inverted viewing condition, only during trial 3.

Trials with the Kraft Replica were quicker than trials with the 2x3 DOF hand controller because of the difference in control system processing time between the two hand controller configurations.

Analyses of Subjective Responses for 2x3 DOF Hand Controller

Analysis for the issue of mental workload revealed marginal significance ($p=.0636$), with the inverted viewing condition requiring more mental workload than the other three viewing conditions. Subjects rated the normal and inverted/reversed viewing conditions as being significantly more acceptable than the reversed and inverted for executing right and left movements ($p<.05$). Subjects rated the normal, reversed, and inverted/reversed viewing conditions significantly better than the inverted viewing condition for overall acceptability, with the normal condition rating significantly more acceptable than the inverted/reversed viewing condition ($p<.01$).

Analyses of Subjective Responses for Kraft Replica Hand Controller

Subjects rated the normal viewing condition as requiring significantly less mental workload than the other three viewing conditions. The reversed viewing condition was also rated as requiring significantly less workload than the inverted viewing condition ($p<.01$). When subjects were asked if their discomfort affected performance, they believed that the inverted condition affected performance significantly more than the

normal and reversed viewing conditions ($p<.05$). The inverted view was found to be the worst for movements in all three axes (up/down, right/left, and in/out). The normal view was found to be significantly more acceptable overall than the inverted and inverted/reversed viewing conditions. In addition, the reversed view was significantly more acceptable than the inverted viewing condition ($p<.01$).

DISCUSSION

The first objective of this evaluation was to determine the effects of reversed, inverted and inverted/reversed views on remote manipulation performance with a 2x3 DOF hand controller. Results showed that while inverted views often produced the slowest times, the only significant difference between the viewing conditions was during the third trial. Trials 2 and 3 were both significantly faster than trial 1, suggesting that a significant amount of learning occurred between trials 1 and 2. Learning may have occurred within each trial, with the largest differences between viewing conditions occurring during the first two subtasks.

Results suggest the same degree of learning occurred at trials 1 and 2 for all viewing conditions, but less learning occurred with the inverted viewing condition than with the other viewing conditions from trial 2 to trial 3. There were no differences among the normal, reversed and inverted/reversed views at trial 3. Subjects may have been able to adapt more readily to the reversed and inverted/reversed views by trial 3.

Even though left and right were transposed in the reversed view, it was often easier to use than the normal view. The views from the camera located behind the manipulator, the normal and inverted views, were partially occluded by the manipulator. This is an unfortunate consequence of placing a camera behind the object that will be used to perform the task. The reversed view provided a complete display with no occlusion from the manipulator.

The inverted view proved to be the most difficult to use, because it not only provided perturbed visual feedback, but also was occluded by the arm. In fact, trials with the inverted viewing condition had the highest average number of unsuccessful grapple attempts with both hand controllers. This was most likely due to the occlusion of the second task piece by the manipulator. Subjects could not determine the specific location of the second task piece, but grappled to test the position of the grippers.

Subjective data for the 2x3 DOF configuration was consistent with performance data: subjects rated the inverted viewing condition significantly lower in overall acceptability over the other three viewing conditions. There was no difference between the normal view and the reversed view, indicating that a reversed view was equally as effective for performing this task.

The second objective of this evaluation was to compare effects of spatially displaced views on remote manipulation with the 2x3 DOF configuration and the Kraft Replica. Results from data collected with the Kraft Replica showed the same order for performance with viewing conditions as the 2x3 DOF, with the normal view being the easiest to use, followed by the reversed view, the inverted/reversed view and the inverted view. Successive trials with the normal and reversed views were shorter in length, where as trial 2 was longer than trial 1 for the inverted and inverted/reversed views. Therefore learning may have been more erratic for the inverted and inverted/reversed views with the Kraft Replica while learning was more constant across viewing conditions with the 2x3 DOF. The normal view was found to be significantly better than the inverted and inverted/reversed views for all three trials, and the reversed view was found to be better than the inverted during the third trial. This suggests that some degree of learning occurred at trial 3 for the reversed viewing condition, but significant amounts of learning did not occur with the inverted and inverted/reversed viewing conditions.

Subjective data for the Kraft Replica showed that the normal view was significantly better than all other viewing conditions. Subjective data for the 2x3 DOF showed that the inverted view was significantly worse than all the other views, and that the normal

view was better than reversed view. These subjective impressions are consistent with task performance, in which trials with the inverted view were significantly longer than trials using the normal view.

From these results, it was hypothesized that the two hand controllers displayed different learning curves. Thus, data was collected to determine the learning effects of successive trials on task performance. The apparatus and procedure followed were the same, with the following exceptions: (1) three new subjects performed six trials of the task, instead of three, (2) subjects practiced trials with the normal view, and only counterbalanced data collected for the perturbed viewing conditions were statistically analyzed, and (3) subjective responses were not collected.

EVALUATION OF LEARNING EFFECTS

Separate ANOVAs were performed on data collected from the 2x3 DOF and the Kraft Replica hand controllers. ANOVAs were performed on data collected with only the perturbed views. Data analysis was not conducted on the normal view completion times because the normal view was not counterbalanced with the perturbed views.

Three separate ANOVAs were performed on completion times for each hand controller. The ANOVAs looked at the following: task completion times across all trials (i.e, if one viewing condition was significantly longer than another for all three trials), task completion times within each trial (i.e, if one viewing condition was significantly faster than another during any one of the three trials), and completion time within each subtask (i.e., if the any of the viewing conditions were significantly different from another viewing condition during any of the four subtasks). Results from analyses performed on subtask completion times were complementary to the other analyses, and thus will not be presented for the sake of brevity. Only significant results will be discussed.

Data collected using the 2x3 DOF showed that there was no difference among the perturbed viewing conditions, but there was a significant difference among the six trials ($p<.05$). The Duncan's test showed that trials 4, 5 and 6 are significantly faster than trials 2 and 3. The learning curves for the six trials are shown in Figure 3. The normal and inverted/reversed viewing conditions seemed more erratic in the first two trials, but quickly became constant. All perturbed viewing conditions appeared to level at trial 4 and remain fairly stable for trials afterward. During trials 4, 5, and 6, the inverted and reversed viewing conditions performed somewhat faster than the normal view, probably because the normal view was the first condition to be presented, for practice.

Results showed that there was no significant difference among the perturbed viewing conditions, but there was a significant difference among the trials ($p<.05$), with the trial 6 being significantly faster than trials 1, 2, 3, and 4. A graph showing the learning curves for each viewing condition with the Kraft Replica is presented in Figure 4. The graph shows that trial completion time for the inverted and inverted/reversed viewing conditions were erratic for all trials. Times for the reversed viewing condition had begun a constant trend toward trial completion time with the normal view.

Data from the 2x3 DOF showed that trials using the inverted/reversed view were longer than other views, but not significantly longer. Trial completion times for all perturbed views also appeared to stabilize during trials 5 and 6, and trials with the inverted and reversed views were somewhat quicker than trials with the normal view.

Data collected using the Kraft Replica showed that all perturbed views took longer than the normal view, even though trials with the normal view were performed first. Trials using the inverted and inverted/reversed views were erratic for all six trials, but trial completion times for the reversed view had begun to stabilize by trials 4, 5, and 6. A comparison of the two hand controllers showed that there was a greater difference between the perturbed views and the normal view when using the Kraft Replica. There was little decrement in

performance between the perturbed views and the normal view with the 2x3 DOF.

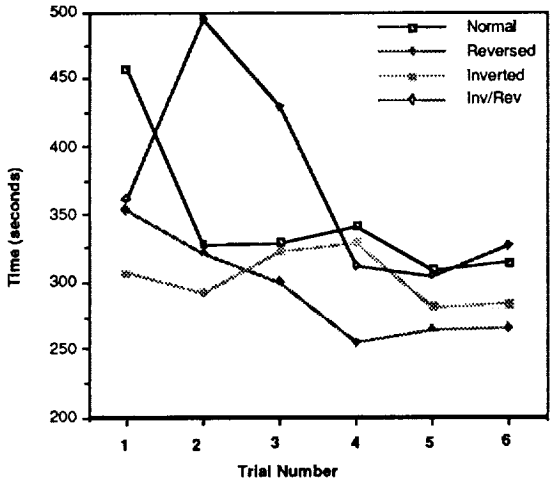

Figure 3. Completion Times for 2x3 DOF Hand Controller (Normal View for Comparison Only)

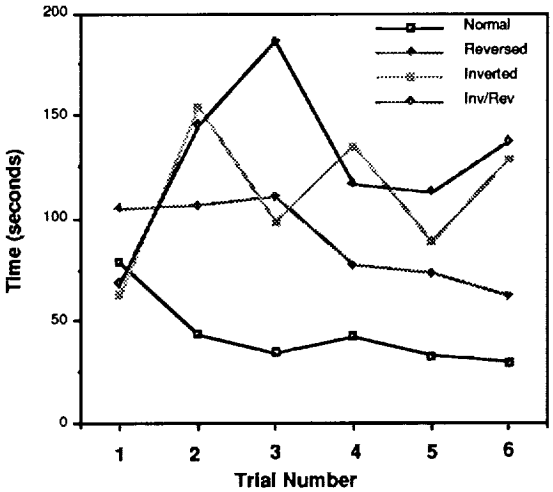

Figure 4. Completion Times for Kraft Replica Hand Controller (Normal View for Comparison Only)

Trials with the perturbed viewing conditions stabilized more with the 2x3 DOF than with the Kraft Replica over the six trials. The inverted and inverted/reversed views were more erratic than the reversed view for both hand controllers, and the reversed view was often quicker than the other perturbed views. Data collected from both hand controllers suggests that learning occurs more steadily with the 2x3 DOF hand controller. Learning may occur quicker with the 2x3 DOF configuration, although there is a limit to the amount of improvement from the initial trial. The processing time of the 2x3 DOF control system configuration limits the speed at which inputs are induced to the manipulator, and this limit may restrict the amount of improvement possible from an early trial to a later trial.

CONCLUSIONS

The purpose of this investigation was to determine the effects of spatially displaced feedback on remote manipulation task performance with two hand controllers. Studies conducted previously had examined spatially displaced feedback with the Kraft Replica hand controller. Since the baseline hand controller for Space Station *Freedom* was deemed to be a 2x3 DOF configuration, it was concluded that studies examining spatially displaced feedback should incorporate 2x3 DOFs.

Across both controllers, the inverted and inverted/reversed viewing conditions were generally more difficult to use than the normal and reversed viewing conditions. Tasks could be performed with the reversed view with little or no decrement in task performance. The reversed view often provided better performance than the normal view, because the normal view could be blocked by the manipulator performing the task.

There were no significant differences among viewing conditions with the 2x3 DOF. The inverted and inverted/reversed views were worse than the normal view with the Kraft Replica. Results also showed that learning was more constant and predictable with the 2x3 DOF configuration. Learning was more erratic with the Kraft Replica, possibly because it was difficult to recover from incorrect inputs. There was more cross-coupling with the Kraft Replica as well, and this hand controller may be more difficult to maneuver with accuracy and precision. This erratic behavior with the Kraft Replica may explain an anomaly in an earlier study performed by Stuart, et.al (1990).

The scope of this study was to examine the use of 2x3 DOF hand controllers for performing tasks with spatially displaced feedback. A host of other considerations need to be evaluated before the issues surrounding perturbed visual feedback can be resolved as listed below :

1. Use of perturbed visual feedback while performing various tasks.

2. Use of perturbed visual feedback when several camera views are provided to perform a task. Generally, more than one view of the task board will be available on space platforms during tasks. If several views are provided, operators may rely less on the perturbed views. If the perturbed views are absolutely necessary for completion of the task, then performance may be degraded.

3. Various types of spatial displacements. The most probable displacements that operators on *Freedom* will have to experience will be angular displacements, either along the vertical or the horizontal axes. These types of displacements need to be studied with tasks similar to those to be performed in space.

4. Investigation of changes in the control mode of the hand controller to be compatible to the camera, where the point of reference would move with respect to the camera. This conversion would place the mental transformation of the perturbed view on the control system, instead of the operator.

REFERENCES

Bernotat, R.K. (1970). *Rotation of Visual Reference Systems and Its Influence on Control Quality*. IEEE Transactions on Man-Machine Systems, Volume MMA-11, No. 2, Page 129.

Kim, W.S., Tendick, F., and Stark L.W. (1987). Visual Enhancements in Pick-and-Place Tasks: Human Operators Controlling a Simulated Cylindrical Manipulator. In *IEEE Journal of Robotics and Automation*, Volume RA-3, No. 5, Page 418.

National Aeronautics and Space Administration (1991). *Space Station Hand Controller Commonality Test Report*. (NASA Report JSC-32125). Man Systems Division.

Smith, K.U., and Smith, W.M. (1962). *Perception and Motion*. W.B. Saunders and Company: Philadelphia.

Stuart, M.A., and Smith, R.L. (1989). *Spatially Displaced Visual Feedback and the Performance of FTS-like Tasks* (NASA Tech. Report JSC-23547). Houston, Texas: NASA Lyndon B. Johnson Space Center.

Stuart, M.A, Bierschwale, J.M., Sampaio, C.E, and Legendre, A.J. (1990). *The Role of Perturbed Sensory Feedback in Space Remote Manipulation Tasks -- Preliminary Guidelines* (NASA Tech. Report JSC-24643). Houston, Texas: NASA Lyndon B. Johnson Space Center.