N89-10090

Consolidated Fuel Reprocessing Program

THE IMPLICATIONS OF FORCE REFLECTION FOR TELEOPERATION IN SPACE*

John V. Draper
Human Machine Interfaces, Inc.
1808 Blue Spring Lane
Knoxville, Tennessee 37932

Joseph N. Herndon
Fuel Recycle Division

and

Wendy E. Moore
Instrumentation and Controls Division
Oak Ridge National Laboratory
Post Office Box X
Oak Ridge, Tennessee 37831

ABSTRACT

This paper reviews previous research on teleoperator force feedback and reports results of a testing program which assessed the impact of force reflection on teleoperator task performance. Force reflection is a type of force feedback in which the forces acting on the remote portion of the teleoperator are displayed to the operator by back-driving the master controller. The testing program compared three force reflection levels: 4 to 1 (four units of force on the slave produce one unit of force at the master controller), 1 to 1, and infinity to 1 (no force reflection). Time required to complete tasks, rate of occurrence of errors, the maximum force applied to task components, and variability in forces applied to components during completion of representative remote handling tasks were used as dependent variables. Operators exhibited lower error rates, lower peak forces, and more consistent application of forces using force reflection than they did without it. These data support the hypothesis that force reflection provides useful information for teleoperator users.

The earlier literature and the results of the experiment are discussed in terms of their implications for space-based teleoperator systems. The discussion describes the impact of force reflection on task completion performance and task strategies, as suggested by the literature. It is important to understand the trade-offs involved in using telerobotic systems with and without force reflection. Force-reflecting systems are typically more expensive (in mass, volume, and price per unit), but they reduce mean time to repair and may be safer to use, compared to systems without force reflection.

*Research sponsored by the Office of Facilities, Fuel Cycle, and Test Programs, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) has embarked on an extensive national project to establish a permanent human-occupied space station in low earth orbit. In order to accomplish this, significant levels of dexterous, human-like handling tasks must be accomplished during orbit. This will include space station construction and planned and unplanned maintenance on space station. In addition, satellite repair and maintenance will be done. To meet the need for sharply increased levels of dexterous handling while decreasing the hours of human extravehicular activity required, NASA plans to utilize telerobotic hardware on the space station. The role of force reflection in these telerobotic systems is an important issue for developing NASA hardware.

The Oak Ridge National Laboratory's (ORNL's) Consolidated Fuel Reprocessing Program (CFRP) is responsible for developing systems for reprocessing nuclear fuel. This effort includes development of advanced systems for remote maintenance of process equipment developed by CFRP. The CFRP emphasis is on teleoperator systems featuring dexterous, force-reflecting servomanipulators, transporters for large-scale movement, television viewing of remote sites, and human-in-the-loop control. Significant research resources have been used by the CFRP to develop and understanding of the implications of force reflection for performance of teleoperators.

Because CFRP systems emphasize human control, the performance of the human operator is important for overall system performance and, in turn, for mean time to repair and plant availability. One important issue in this area is the question of how much sensory information is necessary for efficient performance of maintenance tasks. Monochromatic television seems to be a minimum requirement; enhancements to the system (e.g., color, increased resolution, and/or stereoscopic television) may improve task performance for certain classes of remote handling tasks.[1] Supplementary sensory channels (e.g., hearing or touch) could also be provided.

Force feedback may be one important supplementary sensory channel. Force feedback may be in the form of proportional force feedback or in the form of force-distribution feedback.[2] Force-distribution feedback provides a display of forces which matches the distribution of forces on the manipulator (usually the manipulator end-effector). It gives users a sense of touch, similar to human tactition. It allows perception of shapes and textures in the remote area. Proportional force feedback presents the operator with a display of force which is proportional to forces on the teleoperator. Force reflection is a type of proportional force feedback in which forces applied by the slave (remote) portion of a master/slave teleoperator are displayed to the operator through back-driving the master controller. The user feels forces through the action of the master controller on the teleoperator master handle. Proportional force feedback gives users a sense which is not directly analogous to any single human sense, but combines elements of tactition (touch) with kinesthesia (kinesthesia is the sense related to forces exerted by the limbs and acting on them).

LITERATURE REVIEW

Four studies have made direct comparisons of teleoperator performance with and without force reflection. D. A. Kugath[3] found some evidence for a beneficial effect of force reflection on teleoperator performance (defined as task time and collisions with equipment in the remote area) for simple tasks with a fairly large-scale manipulator (a General Electric CAM 1400 with 12- and 13-ft booms), but, in the author's words, "Not enough data . . . [were] taken to show conclusively that the lack of force feedback was detrimental." For the large manipulator employed, removal of force reflection following completion of a task several times with force reflection led to high rates of operator errors and seemed to cause manipulator instability. Kugath also noticed a change in the style of operation in his subjects when force reflection was removed. Without force reflection, users seemed to execute trajectories stepwise, making a movement and then checking manipulator position before making another input. This was in contrast to continuous motions observed with force reflection and seemed to lead to frequent target overshoots.

J. W. Hill[4] also reported data which seem to favor force reflection (performance was defined as time required to complete tasks), but his force reflection differences are confounded with differences between the manipulators used in the force reflecting and non-force reflecting conditions. In the latter, subjects performed a set of simple tasks with the NASA/Ames Arm, a unilateral system with an exoskeletal master controller and anthropomorphic (elbows-down) stance. In the force-reflecting condition, they used a Central Research Laboratories (CRL) Model H manipulator system, a mechanical master-slave manipulator with a "through-the-wall" stance. These systems seem too different (kinematically and in terms of performance) to be directly comparable, and indeed the author reports that the Ames Arm typically required 20% longer to complete some simple movements.

Hill and J. K. Salisbury, Jr.,[5] performed an experiment that compared a single manipulator system (the French-designed MA-23) with and without force reflection and also found average differences favoring force reflection in the time required to complete tasks. This is the most rigorous study of the topic to date. Unfortunately, the design of this study and the statistical procedures used to analyze its data were flawed. The experiment included only two subjects; they were administered force reflection conditions in reverse order. The sample size leaves the study vulnerable to threats to validity (for a discussion of threats to experimental validity, see ref. 6) from treatment by subject interactions; small experimental groups increase the likelihood that the subjects are not typical of the population as a whole, and they may have an atypical reaction to the conditions of the experiment. The inversion of treatment administration order does not seem adequate protection against treatment by practice interaction. In experiments that make repeated measurements on subjects, the comparison between conditions must be based on a within-subjects difference. In other words, the performance of one subject with force reflection should be compared to his own performance without force reflection. The total difference should be the sum of these within-subjects differences. When the treatment administration order is reversed, it does not account for the within-subject effect of practice. Averaging across subjects (especially when there are only two) will not remove the effect because individuals learn at different rates and to different final performance levels. Furthermore, the data analyses used in the study were not appropriate. The authors used a simple factorial analysis of variance (ANOVA) model and assumed that all factors in the model were fixed factors. With repeated measurements on the same subjects, this is not appropriate. A model that considered subjects to be a random factor (a within-subjects model) is the correct one in this case. The mean square ratio (or F test) the authors used for the test of the main effect of force reflection had 1 and 504 degrees of freedom (D.F.); it had the mean square for the force reflection effect as its numerator and the mean square for error as its denominator. The appropriate test would use the mean square for the subject by force reflection condition interaction as its denominator, and would have only 1 denominator D.F. The results of the tests used by the authors are uninterpretable, and conclusions based on this study cannot be accepted with any confidence.

In a more recent study, data collected at ORNL in the course of teleoperator system comparisons failed to demonstrate any positive effect of force reflection on the performance of remote handling tasks.[7] The differences between tasks completed with and without force reflection using two different teleoperator systems were not statistically significant, although on average users required longer to complete tasks with force reflection than they did without it. However, the tasks and procedures used in that experiment were not designed to evaluate force reflection and may have been insensitive to its effects. The ORNL experiment compared a wide range of teleoperator systems, and tasks were designed to be simple enough to complete with relatively low-dexterity systems. Force information had no impact on efficiency within these simple tasks.

J. C. Bliss, Hill, and B. M. Wilber[2] studied performance of tasks with force-distribution feedback. These authors did not find significant differences in the rate of task performance with and without force-distribution feedback. However, the quality of performance, both in terms of the number of errors and failed attempts at the task and in terms of the strategy used by operators was different between the force feedback conditions. These authors had subjects perform a set of tasks with and without force feedback, and with varying degrees of occlusion of the camera line of sight. Without the force-distribution feedback, there were no differences in performance when operators had unobstructed views of the task. With increasing occlusion of the camera view, the number of failed attempts to grasp and operate task components increased more rapidly for users without force feedback. In addition, users without force feedback made more attempts to grasp components and were less careful. Users with force feedback tended to position the teleoperator more carefully. These users made fewer attempts per successful completion of the task, but because they were more careful (and more precise) about teleoperator position, their attempts tended to be of longer duration. Although there were no differences in the mean time to complete the tasks, the quality of performance differed between force-feedback conditions. Without force feedback, users made frequent imprecise attempts to grasp and operate task components; users with force feedback made fewer attempts, and their attempts were more precise and longer in duration.

CONCLUSIONS FROM THE LITERATURE

It is impossible to draw precise conclusions concerning the effect of force on task performance from the studies which compared teleoperator performance with and without it. The results of these studies are uninterpretable because of their methodological inadequacies. However, certain hypotheses may be stated based on observations from this literature and on the characteristics of humans as processors of information. First, information provided by force reflection can be unique, or it can complement information available through other sensory channels. For example, an operator attempting to tighten a bolt to a criterion torque may be able to judge when the bolt reaches this torque by feeling the reflection of resistance to turning. The task can also be done by viewing the dial of a torque wrench. When force reflection provides information that complements operators' television views of the remote area, operators are not as likely to attend to force reflection since humans tend to favor vision over the other senses.[8] Force reflection is most helpful when it displays information that other senses (particularly vision) are unable to provide or when other displays are difficult to interpret. The greatest advantage for force reflection should occur when forces applied to the remote area are important; when task components require guidance or assembly in areas difficult to see with television cameras; and when viewing is degraded by dust, gases, lens browning, or other obscuration.

Second, there appear to be fundamental differences in the strategies employed by operators with and without force reflection. Kugath reports stepwise trajectory inputs without force reflection; Bliss, Hill, and Wilber report different approaches to grasping task components. It seems that operators without force reflection perform tasks more tentatively than they do with force reflection. The ability to detect contact through force reflection may give the operators a greater feeling of safety during operations. It may also allow operators to moderate force applied to task components as they work, so that they do not need to avoid contact.

The experiment described in this paper was concerned with the hypotheses that force reflection is helpful when it provides information that cannot be acquired through vision and when forces applied to tasks are important. The hypotheses were tested in a realistic remote maintenance simulation.

METHODS

The Remote Operations and Maintenance Development (ROMD) facility, which is located at the ORNL, was the site of the experiment. The ROMD facility ;ts of a high-bay remote handling demonstration area filled with prot:al process equipment and teleoperator systems, along with a control for teleoperators and other remotely controlled equipment. Detailed ,ptions of the ROMD facility may be found in refs. 9 and 10. The CRL M-2 manipulator, which was used in the experiment, is housed in facility. The CRL M-2 has a digital control system that allows so: control over force-reflection levels and which provides a means fcck switching between force levels. Details of the CRL M-2 and iitrol system may be found in ref. 11. In this experiment, operators the M-2 with 4 to 1 (four units of force at the slave produces ait of force at the master controller) force ratio, 1 to 1 force ratiid without force reflection.

Four ; were included in the testing. The tasks were representative of c:al plant remote maintenance tasks requiring dexterity to complete. ıre 1 is a photograph of the tasks and task framework. The task f.work is mounted on a force-torque table. Task 1 consisted of assembl: two pairs of electrical connectors. Two sockets were mounted on of a plate attached to the top of the task framework, and two more weounted underneath the top plate. To start the task, the connectors: placed on top of the task framework. The operators picked up tonnectors and plugged the ends into the sockets. After inserting afour connectors, the operators unplugged the connectors and replaceiem on top of the task framework.

Task 2sisted of a peg-in-hole task mounted within the task framework. : hole was mounted at a 15° elevation and was offset to the left 15:om the sagittal plane of the task framework. The high end was clot to the teleoperator package and canted toward the left side (facinne task framework) of the package. The task was started with the pefully inserted in the hole. Operators removed the peg, touched the sk framework with the end of the peg, and reinserted it.

Task 3 ısisted of a pair of stainless-steel tubes with Swagelock-type tubing :tings. One pair of fittings was mounted on vertical plates on thop of the task framework. These plates were mounted 45° to the sagitl plane of the task framework and 90° to each other. The other pair o:ittings was mounted on a plate attached to the side of the framewori The plate on the side of the framework was tilted 30° to the horizont: baseplate and 30° to the vertical side of the task framework. The fnt (closest the teleoperator when it is in position to perform the tks) and outside (farthest from the framework) edges of this plate we: lower than the back and inside edges. To begin the task, the jumr tubes were placed on top of the task framework. The operators pic:d up the jumper tubes, inserted the ends in the appropriate socket: and tightened the tubing fittings with a wrench. The wrench was pl:ed on the top of the task framework at the beginning of the task.

Task 4 casisted of a 3/4-in. nut welded to the plate on top of the task frameworl and an accompanying 3/4-in.-diam, 3-in.-long bolt. Operators screwed te bolt into the nut to a criterion depth. At the start of the task, the bolt was placed on top of the task framework near the vertical plate to which the nut was attached. The operators picked up

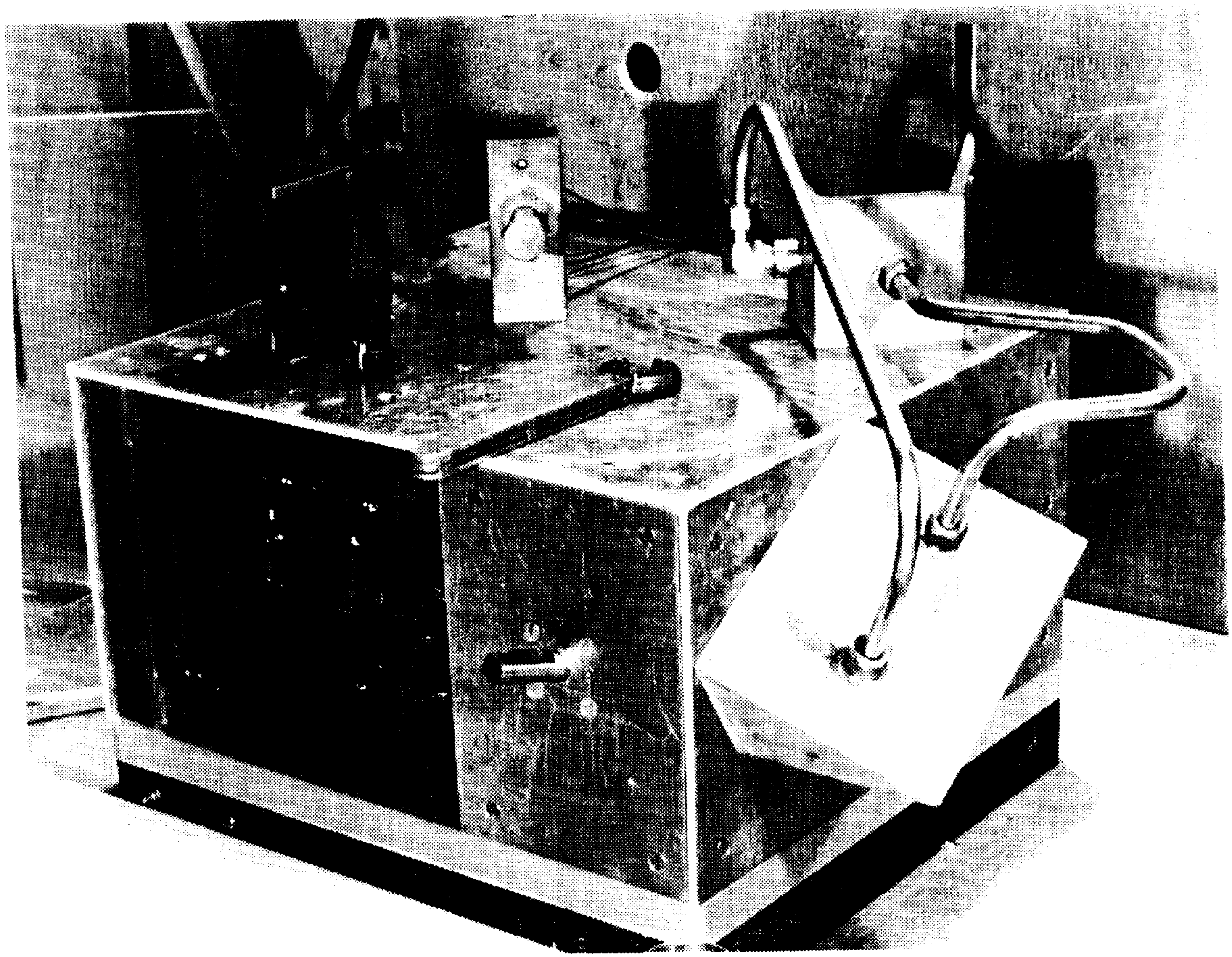

Fig. 1. Task framework, tasks, and load table.

the bolt, positioned it in the nut, and rotated it until it engaged the nut. The operators continued rotating the bolt until the criterion depth was reached. A light mounted on the task framework above the nut indicated when the criterion depth was reached.

Six qualified (according to standard ROMD facility training procedures) teleoperator users participated in the experiment. Every operator completed 1.5 h of practice prior to the start of testing, 0.5 h with each force-reflection level. After the practice sessions, each operator completed 15 testing sessions. A testing session consisted of six trials, two each with three experimental tasks (electrical connectors, peg-in-hole, and tubing jumpers tasks). Within sessions, task were administered in random order under the constraints that no task would be completed consecutively and no task would be repeated before each task had been done once. Six of the 15 total sessions also included one repetition of the bolt threading task. A rest period of at least 1 h between consecutive sessions for one operator was required, and no more than 96 h were allowed to elapse between testing sessions for an operator. These restrictions prevented operators from becoming overly fatigued or out of practice.

Television views were restricted to those available from cameras on board the M-2 package (see refs. 9 and 10). Two cameras were set up to give views from approximately 45° to either side of the tasks (outboard of the sagittal plane of the teleoperator). Operators were allowed to use either of these views and/or a camera view from between the teleoperator arms. Operators were not allowed to see views from cameras other than those onboard the M-2 package during trials, and they were not allowed to change the aiming, magnification, or position of cameras.

Three categories of dependent variables were recorded. The rate of task performance was measured by recording the time in seconds required to complete tasks, the quality of task performance was measured by recording the frequency of occurrence of each of 18 different types of errors, and the effect of the teleoperator on the remote area was measured by recording the forces applied to task components. This multimethod approach to performance quantification avoids bias which may result from defining performance as only one variable. Data were recorded using a Hewlett-Packard 9236 computer programmed in Multi-FORTH to scan 21 channels of A/D information and store the data on a hard disk/streaming tape drive system. Errors included 18 items such as collisions, dropping grasped items, items slipping in the grasp of the teleoperator, collisions, damage to teleoperator or task. A complete list may be found in ref. 7. Forces, torques, velocity of each joint of the right-hand slave, and motor currents of selected joints were recorded 20 times per second. Force and torque data were provided by the load table on which the tasks were mounted. These data were later reduced to resolved force and torque values for each data point. Preliminary analysis of force and torque data revealed that the correlation between these variables was high (for average force and average torque, $r = 0.78$; for maximum force and maximum torque, $r = 0.82$) and the averages and standard deviations of the two variables were similar (average force = 5.23, standard deviation = 2.58; average torque = 4.76, standard deviation =

2.11). These variables seemed to be measuring the same dimension of performance, so the torque data were not included in the statistical analyses.

RESULTS

This paper will concentrate on the results of analyses conducted on the time required to complete each task (converted to its logarithm to base 10), the rate (per minute) of errors, the maximum force exerted, and the force variance within each task repetition. The last variable is a measure of the consistency with which operators apply forces in the remote area. High scores indicate inconsistency in force application, and low scores indicate uniform use of force throughout a task repetition.

The dependent variables were submitted to repeated-measures multivariate analysis of variance.[12] Separate analyses were performed for each task. Details of the statistical analyses may be found in ref. 13. This paper will summarize results of the comparison between force reflection levels. In the sections to follow, significant effects of force reflection will be described but details of the tests will not be reported. The significance level of F tests (the statistic calculated by MANOVA and ANOVA) in the analysis was alpha <0.05 (alpha is the probability of making a mistake in declaring two averages different). Figures 2, 3, 4, and 5 illustrate the averages of each variable for the task and force level combinations.

ELECTRICAL CONNECTOR TASK

The MANOVA found a significant overall impact of force reflection for the electrical connector task. The ANOVA found this effect to be significant for the maximum force and force variance variables. Operators had higher peak forces and larger variance in forces without force reflection than they did with it. There was not a significant difference between 4:1 and 1:1 levels, although on average both variables were lower than in the nonforce condition.

The test for time to complete was very close to significance, with F reaching the 0.06 alpha level. On average, operators completed this task in less time with 4:1 than with either other level.

PEG-IN-HOLE TASK

The MANOVA found a significant overall impact of force reflection for the peg-in-hole task. The ANOVA found this effect to be significant for the error rate, maximum force, and force variance variables. Operators had higher error rates, higher peak forces, and larger variance in forces without force reflection than they did with it. There was not a significant difference between 4:1 and 1:1 levels.

TUBING JUMPERS TASK

The MANOVA found a significant overall impact of force reflection for the tubing jumpers task. The ANOVA found this effect to be significant for the error rate, maximum force, and force variance variables.

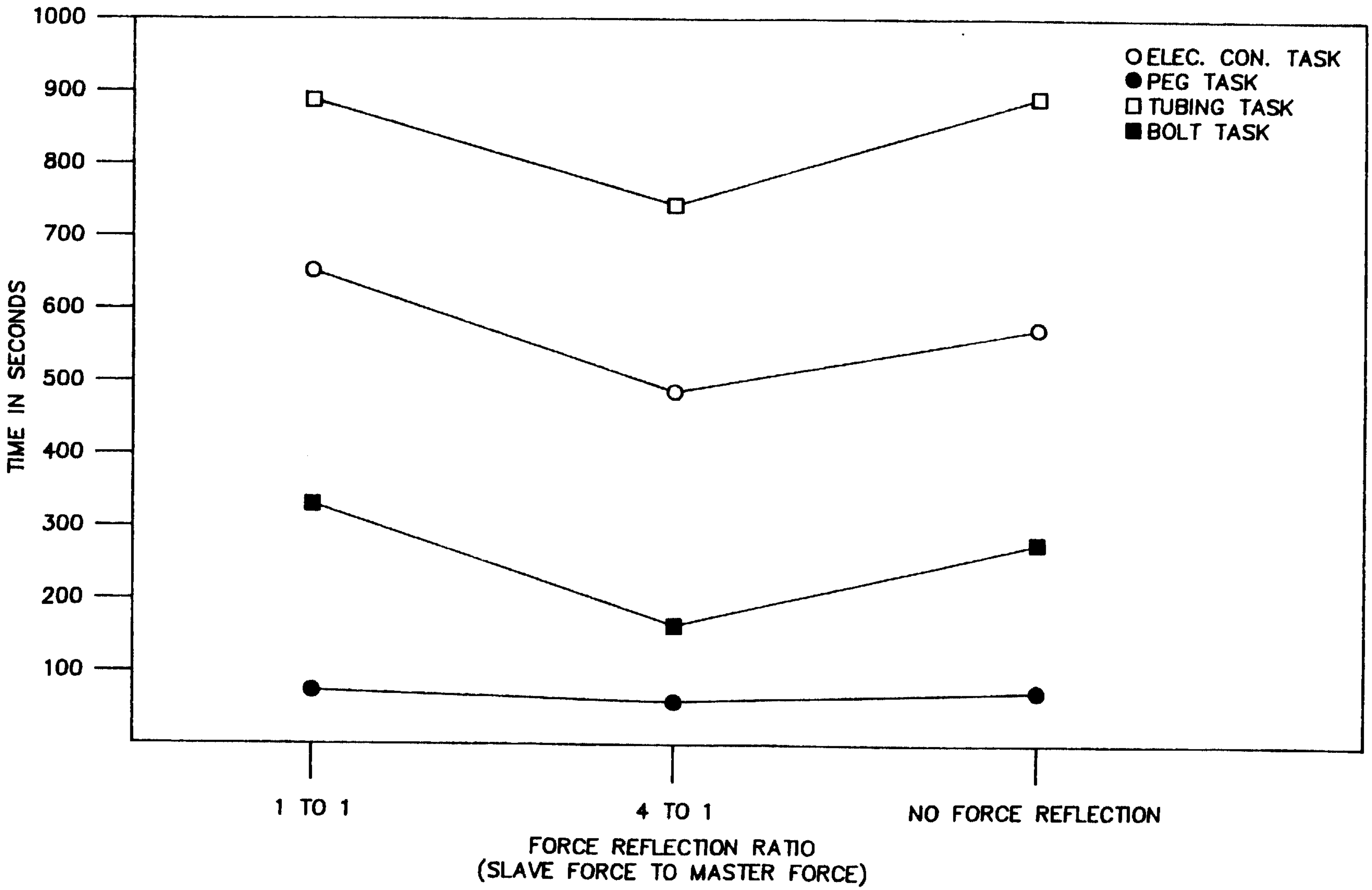

Fig. 2. Average time required to complete tasks.

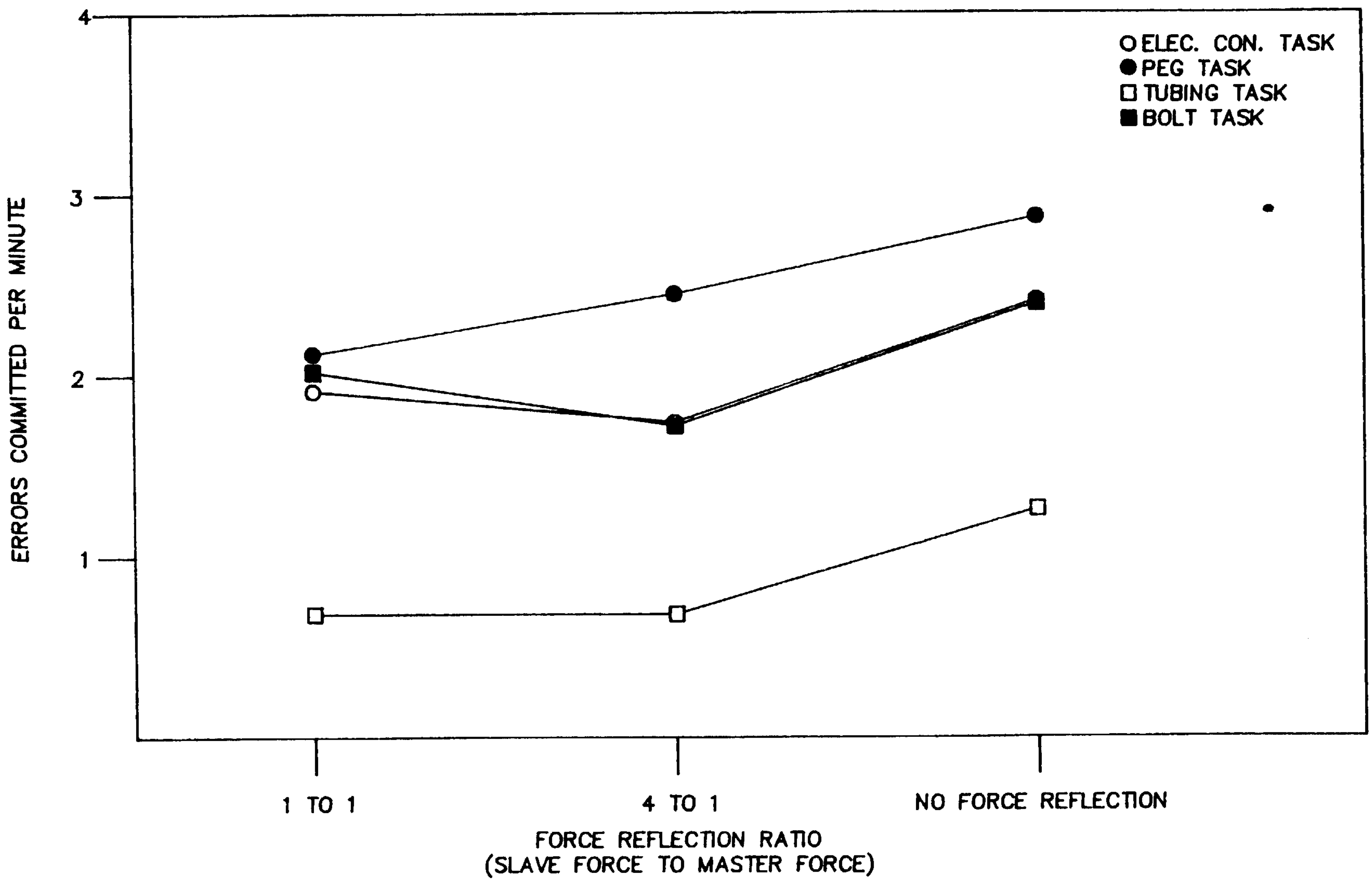

Fig. 3. Average rate of error occurence.

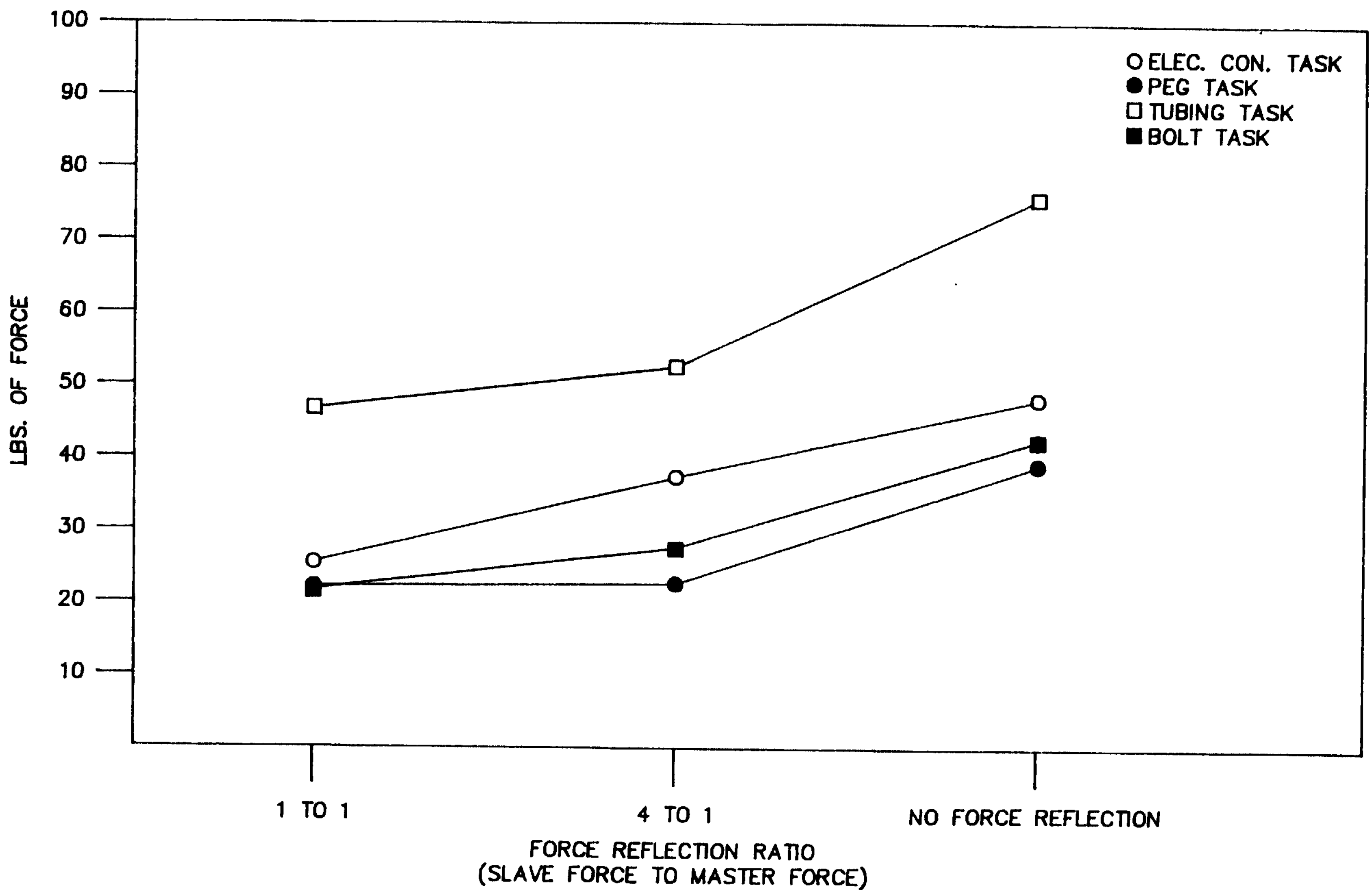

Fig. 4. Average of maximum force per task repetition.

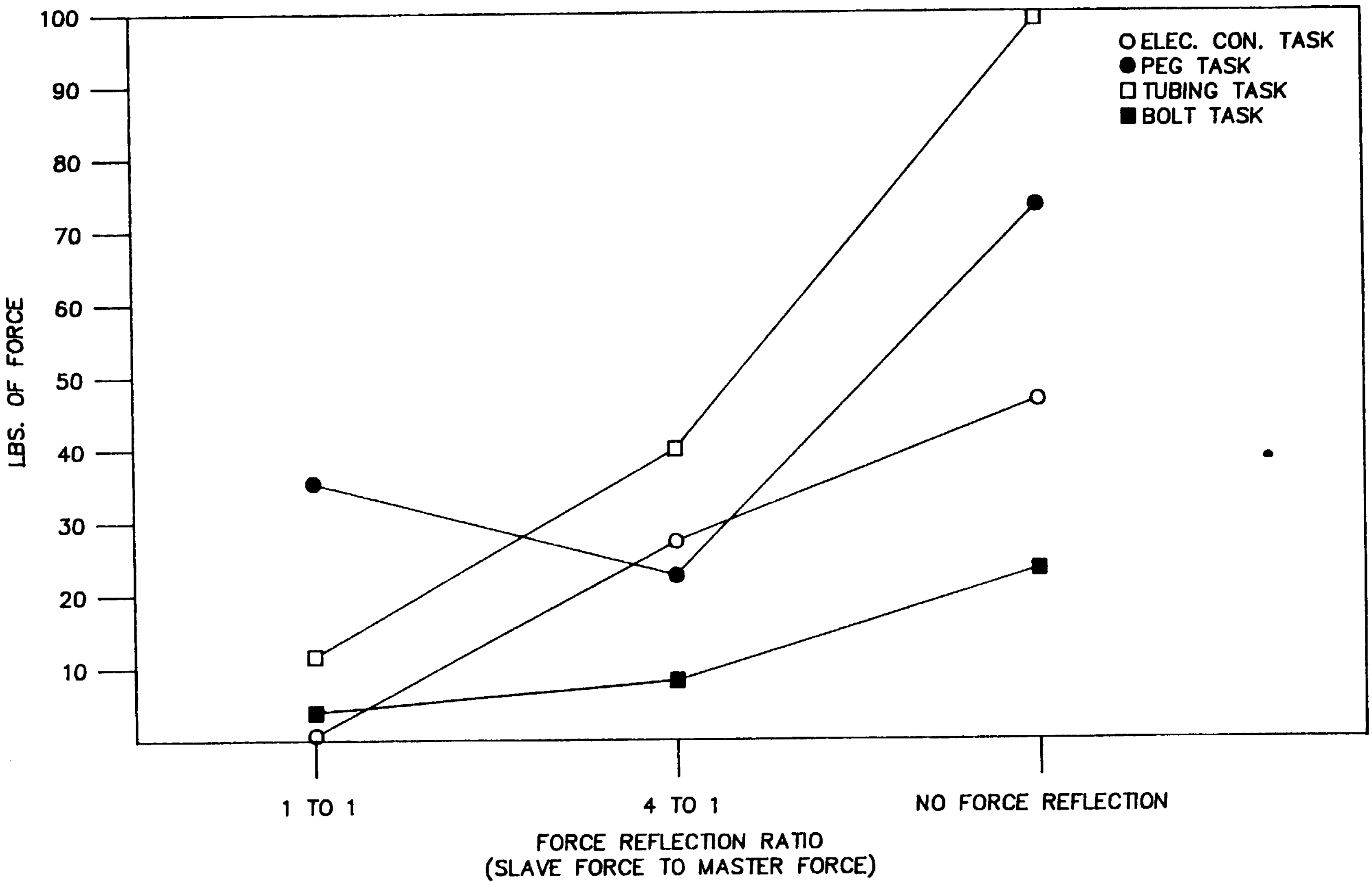

Fig. 5. Average reliability of exerted forces per task repetition.

Operators had higher error rates, higher peak forces, and larger variance in forces without force reflection than they did with it. There was not a significant difference between 4:1 and 1:1 levels.

The test for time to complete was very close to significance, with F reaching the 0.07 alpha level. On average, operators completed this task in less time with 4:1 than with either other level.

BOLT-THREADING TASK

The MANOVA found a significant overall impact of force reflection for the bolt-threading task. The ANOVA found this effect to be significant for the maximum force and force variance variables. Operators had higher peak forces and larger variance in forces without force reflection than they did with it. There was not a significant difference between 4:1 and 1:1 levels.

OPERATOR FATIGUE

Force reflection adds to the friction and inertia experienced by operators using teleoperators. Therefore, it can have an adverse impact on teleoperator ease of use. This could lead to greater operator fatigue while using force reflection, particularly if friction and inertia are high. However, comparison of performance of tasks the first and second time within testing sessions found no evidence of greater operator fatigue associated with force reflection in these data. This may result from to the low friction and inertia characteristic of the M-2 manipulator.

CONCLUSIONS

These data support the hypothesis that force reflection can be beneficial for operators performing remote handling tasks, when the information it provides has no visual analog (operators were unable to gauge deflection or other signs of force in this experiment). It can be particularly useful when forces in the remote area must be controlled. In general, force reflection allowed operators to complete the tasks in this experiment with greater efficiency than they did without force reflection. The time required to complete tasks was not significantly reduced by force reflection (the results are affected by an operator by force reflection condition interaction), but for two of the four tasks the presence of force reflection led to significantly lower error rates. For all four tasks, force reflection allowed the operators to reduce peak forces applied to task components and to be more consistent in the application of forces. Even if there is no difference in task completion time, maintenance campaigns conducted with force reflection can be expected to be completed more quickly than those conducted without it. Operators are less likely to cause damage to equipment during maintenance with force reflection because they are better able to control forces. In addition, operators using force reflection commit errors at a lower rate. These findings are especially important for teleoperation in space. Control of exerted forces will be much more important in space-based remote operations because of the presence of fragile equipment and the necessity of avoiding unwanted dynamic effects. In addition, operator errors in space will be more difficult to recover from than in terrestrial applications.

It should be noted that the results presented in this paper represent the performance of experienced operators performing familiar tasks. These data do not address the possible impact of force reflection on novice operators or on experienced operators performing novel tasks. It may be postulated that force reflection will be beneficial under these conditions as well, but there are no data to support that hypothesis at this time.

REFERENCES

1. J. V. Draper, Y. Fujita, and J. N. Herndon, Evaluation of High-Definition Television for Remote Task Performance, Oak Ridge National Laboratory, ORNL/TM-10303, April 1987.

2. J. C. Bliss, J. W. Hill, and B. M. Wilber, Tactile Perception Studies Related to Teleoperator Systems, National Aeronautics and Space Administration, NASA CR-1775, April 1971.

3. D. A. Kugath, Experiments Evaluating Compliance and Force Feedback Effect on Manipulator Performance, National Aeronautics and Space Administration, NASA-CR-128605, August 1972.

4. J. W. Hill, Study of Modeling and Evaluation of Remote Manipulation Tasks with Force Feedback, National Aeronautics and Space Administration, NASA-CR-158721, July 1979.

5. J. W. Hill and J. K. Salisbury, Jr., Study to Design and Develop Remote Manipulator Systems, National Aeronautics and Space Administration, NASA-CR-152092, November 1977.

6. T. D. Cook and D. T. Campbell, Quasi-Experimentation: Design and Analysis Issues for Field Settings, Houghton Mifflin Company, Boston, 1979.

7. J. V. Draper, S. J. Handel, E. Sundstrom, J. N. Herndon, Y. Fujita, and M. Maeda, Final Report: Manipulator Comparative Testing Program, Oak Ridge National Laboratory, ORNL/TM-10109, February 1987.

8. C. D. Wickens, Engineering Psychology and Human Performance, Charles E. Merrill Publishing Company, Columbus, Ohio, 1984, p. 253.

9. J. N. Herndon, "The State-of-the-Art Model M-2 Maintenance System," Proceedings of the Robotics and Remote Handling in Hostile Environments National Topical Meeting, American Nuclear Society, Gatlinburg, Tennessee, April 23-27, 1984.

10. T. W. Burgess, "The Remote Operation and Maintenance Demonstration Facility at the Oak Ridge National Laboratory," Proceedings of the International Topical Meeting on Waste Management and Decontamination and Decommissioning, American Nuclear Society, Niagara Falls, New York, September 14-18, 1986.

11. P. E. Satterlee, H. L. Martin, and J. N. Herndon, "Control Software Architecture and Operating Modes of the Model M-2 Maintenance System," Proceedings of the 1984 National Topical Meeting on Robotics and Remote Handling in Hostile Environments, American Nuclear Society, Gatlinburg, Tennessee, April 1984.

12. R. E. Kirk, Experimental Design, 2d ed., Brooks/Cole Publishing Company, Belmont, Calif., 1982.

13. J. V. Draper, S. J. Handel, W. E. Moore, J. N. Herndon, and E. Sundstrom, Final Report: Force Reflection Testing Program, Oak Ridge National Laboratory, in preparation.