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NASA Technical Memorandum 107569

Telerobotic Hand Controller Study of Force Reflection with Position Control Mode

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March 1992

National Aeronautics and
Space Administration

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TELEROBOTIC HAND CONTROLLER STUDY OF FORCE REFLECTION WITH POSITION CONTROL MODE

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ABSTRACT

To gain further information about the effectiveness of kinesthetic force feedback or force reflection in position control mode for a telerobot, two Space Station related tasks were performed by eight subjects with and without the use of force reflection. Both time and subjective responses were measured. No differences due to force were found, however other differences were found, e.g., gender. Comparisons of these results with other studies are discussed.

INTRODUCTION

NASA Langley Research Center recently has completed a comprehensive study of the influence of various control input devices and control schemes on the performance of humans in the operation of a remote manipulator. This paper presents data and analysis from a subset of that work which focused on the influence of kinesthetic force feedback with a scaled replica-type controller operating in a position control mode for two space related tasks.

Spurred by Space Station Freedom teleoperation system development plans, kinesthetic force feedback, or force reflection has been investigated several times in recent years (O'Hara, 1987; Hannaford et al., 1989; Das et al., 1991). Force reflection means that the operator "feels," through the input control device or hand controller, the forces acting on the end-effector of the telerobot. These studies included a variety of tasks, input control devices or hand controllers, and control modes.

One of the more recent studies was performed by NASA Johnson Space Center (Stuart et al. 1991). They conducted a hand controller commonality study to evaluate proposed hand controller configurations for three types of Space Station Freedom (SSF) manipulator systems: the Space Station Remote Manipulator System, a free flyer, and the Flight Telerobotic Servicer (FTS). Several hand controllers with various configurations were evaluated using astronauts and other experienced operators performing both software and hardware simulated SSF tasks. Of particular interest to this paper, is the portion of that study performed in the Remote Operator Interaction Laboratory (ROIL), which used a Kraft hydraulic six degrees-of-freedom manipulator system representing FTS. ROIL found significant differences in task completion time for only the Kraft hand controller, although this experimental condition was confounded with manipulator system differences. No difference was found for any of the other hand controllers with or without force reflection in position mode. Part of this reason may be that the tasks were not sensitive to force reflection.

The present study was devised to provide more data on force reflection with position control for two SSF type tasks using the Kraft hand controller operating a non-Kraft manipulator. The two tasks selected for the current study were similar to those used by ROIL but were modified to be more realistic and possibly more sensitive to force reflection. Also, this study used inexperienced subjects to avoid any preconceived biases that may have been present in previous studies which used experienced subjects (Stuart et al., 1991; Molino et al., 1991).

While objective criteria such as task completion time is important, the inclusion of subjective measures allows a more comprehensive evaluation of experimental conditions, because differences in perceived workload may affect people's performance. Wierwille and Casali (1983) validated the MCH scale, a modified Cooper-Harper (1969) scale, and recommended it for overall mental workload assessment. Nygren (1991) evaluated the Task Load Index developed at NASA Ames Research Center (Hart & Staveland, 1988) and supported its potential as a general predictor model for subjective workload. Previous studies have used either one or the other of these measures (Stuart et al., 1991; Merriken & Brown, 1991). Both of these measures were used in the current study and compared with task completion time to allow better comparison of these techniques, particularly as applied to telerobotic tasks. The remainder of this paper will describe the study, the results, and discuss their implications.

METHOD

Subjects

Eight undergraduate engineering students (four males and four females) from a local university participated as paid subjects. They were between the ages of 21 and 32 years (mean age of 24.25 years). All were right handed, and none had any previous manipulator operation experience. These subjects were selected after performing within a specified minimum level on an eye-hand coordination screening task.

Equipment and Facilities

This study required a manipulator system, hand controller, and a operator control station. Each of these are described in this section.

The Laboratory Telerobotic Manipulator (LTM) was chosen for this study (Hankins and Mixon, 1990) and is pictured in figure 1. It is a dual arm, bilateral force-reflecting master/slave system. However, for this experiment, a Kraft mini-master controller was used instead of the full-size LTM Master for human control input. The LTM remote slave arms each have three arm segments. At the junctions between each of the segments, two degrees-of-freedom (pitch and yaw) are provided. An additional roll degree-of-freedom is supplied at the wrist. The end-effector is the parallel-jaw type. A force/torque sensor located at the wrist provided feedback to drive the Kraft controller in the force reflection mode.

The Kraft controller has six degrees-of-freedom and is backdrivable in all but wrist roll. It has a button on the grip for indexing or re-referencing and a rocker switch to open and close the end-effector jaw grippers. The version of the Kraft hand controller used in this experiment had no motor for wrist roll, making the Kraft controller a five degree-of-freedom manipulator for backdriving purposes. Thus, force reflection was implemented as three Cartesian forces and two torques at the wrist proportional to the corresponding sensed forces at the LTM end-effector. The hand controller and LTM arm were started in the same relative configuration. Translation and rotation of the hand controller commanded the LTM arm to move similarly.

The control station consisted of the hand controller and the television monitors for visual information. Both the control station and the Kraft hand controller are shown in figure 2. Four color video monitors were located on the control station, three horizontally along the centering of the station and one above the center. The left and right centerline monitors presented views from the left and right cameras, respectively, mounted on booms at the slave shoulder level. The view from a small camera attached to the end-effector was presented in the middle centerline monitor. The remaining monitor provided an overall front and side view of the task area from a camera located near the laboratory ceiling.

Experimental Tasks

Two different tasks were used to simulate the actions required to perform basic space-application tasks. The dual-peg insertion task was a compliant task representative of insertion and removal of orbital replacement units (ORU). The other task was representative of thermal blanket manipulation. Each of these tasks were comprised of four subtasks and are pictured in figures 3 and 4, respectively.

For the dual-peg task, an ORU was simulated by two pegs attached to a Plexiglas plate on which a handle for the end-effector was fixed. To perform the dual-peg task, the subject was required to manipulate the end-effector to grasp the handle; extract the simulated ORU from one face of the task board; rotate it 90 degrees about the end-effector roll axis, translate it to the other face of the board (which required a plane change); align it with a second set of holes and insert it. The angle between the board faces was 130 degrees, and the distance along the board faces between the hole pairs was 38.5 inches. The peg-to-hole tolerances were .02 inches.

The 13-inch square thermal blanket was attached to an 18 X 13- inch board by 1-inch strips of velcro along two opposite ends of the blanket, which was composed of layers of thin aluminized mylar with a total thickness of 1/16th inch. One end of the blanket was intended to stay attached to the middle velcro strip to form a pivot about which the blanket could move for attachment to either side. There was an additional velcro strip at the edge of the board for this purpose. The task was to align the jaws of the end-effector with a tab along the left edge of the blanket and to grasp it with the end-effector; peel back the blanket from the velcro, translate approximately 21 inches, attach it to the far velcro strip and release the tab; translate to and touch the center of the board with the end-effector closed, translate back to the tab at the far edge and align the end-effector gripper; regrasp the tab and reattach the blanket on the original velcro strip.

Questionnaire

Each subject completed a self-paced, computerized, questionnaire. Part I produced a mental workload rating between 1 and 10. It was similar to a Cooper-Harper type scale (Cooper and Harper, 1969) and had been used previously by Wierwille and Casali (1983); Stuart et al., (1991); Molino et al., (1991). Part II was a series of ten questions for particular hand controller test conditions producing ratings from "completely unacceptable" to "completely acceptable" or -3 to +3 on a scale. Two additional questions assessed discomfort experienced while performing the task and used a unipolar scale of 0 to 6. Part III was the Task Load Index, a metric developed by Hart and Staveland (1988) at NASA Ames Research Center in which ratings from low to high were indicated by the selection of a point between low and high on a bar for each of six workload dimensions: mental demand, physical demand, temporal demand, effort, performance success, and frustration level. Part IV was a series of paired comparisons for the six dimensions of the Task Load Index which were used as weights to derive a total taskload score for each task.

Procedure

Each subject was instructed and tested individually over several test sessions (average number equaled three sessions). A test session was typically 3 hours with breaks provided between test conditions. Upon the subject's arrival to the laboratory, he or she was acquainted with the LTM and control station. Then, the first task to be performed was explained followed by an explanation and demonstration of the Kraft hand controller device.

The subject performed practice trials for that task with either force reflection or no force reflection until a predetermined criterion was reached. Once the subject could perform the task within 10 minutes (with no more than five trials but at least two trials), the subject performed the task three more times. Up to two trials were allowed to be repeated if system malfunctions or other problems occurred. Following the third trial, the subject completed a self-paced questionnaire, described above. The subject was then given instructions for the second task, practiced it as before, performed it three times, and completed the questionnaire.

Subjects were not allowed to practice the last two conditions, which were the two tasks performed using either force reflection or none, whichever he or she had not used for the first two conditions. They went straight into the three recorded trials, followed by the questionnaire, including the final portion (Part IV). After all experimental conditions and questionnaires were completed, the subjects ranked all of the conditions from hardest to easiest and were debriefed.

Dependent Measures

The dependent measures for this experiment were the task completion times for each trial and the questionnaire responses described above. The task times were collected by a computer recording system. To indicate start and stop times, the person serving as data collector pressed a keyboard button. The data collector also noted time with a stopwatch as a backup and any unusual occurrences during a trial.

Experimental Design and Analysis

The experimental design for this study was a 2 X 2 X (2 X 2 X 3) design with two between-group variables and three repeated variables within subjects. The between-group variables were two levels of gender and two levels of practice (force reflection practiced or not). The three repeated variables were two levels of task (dual peg-in-hole and thermal blanket), two levels of force information (force reflection and none), and three trials. All test conditions were presented in counter-balanced orders. The assumptions of normality were checked for the data and upheld. The variable called trials was of no particular interest, because no strong learning curve was evident (no significant difference was shown between trials). Thus, an average time for the subject's three trials was used for further analysis.

Analysis of variance for repeated measures and correlations among the questionnaire responses and between them and the time variables were analyzed to test the following hypotheses: Both performance and subjective workload of two tasks were significantly different when done with force reflection than when done without force reflection by a Kraft hand controller in position mode.

RESULTS

Task completion time

For each condition, task completion time was measured. Total task completion time per trial was analyzed by a repeated measures analysis of variance for a mixed model. The model included the effects of gender, practice, force, task, and trials and their interactions. The null hypothesis of no difference between force reflection and no force for the two tasks was not rejected. Although there was not a significant main effect or interaction effect for force with any other variable at the $p < .05$ level, there was a trend that both tasks were performed more quickly without force reflection, as shown in figure 5. The average task completion times for the thermal blanket without force reflection was 7.11 minutes and with force reflection was 8.05 minutes. The corresponding times for the dual-peg task were 8.96 minutes and 9.23 minutes.

Surprisingly, there was an interaction effect for gender and task, $F(1,4)=7.822$, $p < .05$. As illustrated in figure 6, the females performed the thermal blanket task in an average of 5.68 minutes which was quicker than the males' average performance of 9.47 minutes. Both genders performed the dual-peg task within about the same time. Supporting this significant interaction, were significant main effects for gender $F(1,4)=8.552$, $p<.05$ and for task $F(1,4)=7.822$, $p<.05$. No other interactions or main effects were significant. To try to explain the significant gender by task completion time interaction found earlier, further analyses examined the relationship between gender, handsize, and hand controller movements. No significant correlations were found for these variables with gender.

Subjective responses

Analyses of variance were performed for the mental workload ratings and for each individual question using mixed models including gender, force, task, and their interactions. The mental workload ratings did not differ significantly by gender, force or task condition. However, four of the individual questions had significant task main effects. For all four of these questions, the Kraft hand controller was found to be significantly more acceptable for performing the thermal blanket task than for the dual-peg task in the areas of translation, single axis movements, fine movement, and grip acceptability. The respective significant F-values are $F(1,6)=7.74$, $F(1,6,)=6.39$, $F(1,6)=11.37$, $F(1,6)=7.74$, all for $p<.05$. One question on mechanical feel acceptability differed significantly by force, $F(1,6)=7.71$, $p<.05$, which showed that the Kraft with force reflection was more acceptable in terms of its mechanical feel than without force reflection for both tasks. This illustrates that the subjects were aware of the force being reflected through the hand controller even though it did not affect their task completion times.

The six dimensions of the Task Load Index were also analyzed individually with analysis of variance with the same mixed model. No significant differences were found for any dimension for any of the variables or interactions. In addition, there was no difference between the total Task Load Index measures for the two tasks as measured by a *t*-test, $p < .05$.

To get an idea of what contributed to the variance of the task conditions, factor analyses were performed with all of the subjective data by condition along with gender, handsize, and task completion times. For all conditions, seven principal components were identified. After rotation, the first three components accounted for between 54.64 and 61.33 percent of the variance for that condition. The questions concerning the hand controller movements or characteristics tended to account for significant variance in the two thermal blanket conditions (force and no force) but did not show up within the first three components for the dual-peg conditions. For the dual-peg conditions, the task load related variables constituted the first component. For all conditions, handsize variables made up the third component.

Overall ranks of the conditions were tested by a Friedman analysis of variance for ranks in repeated measures designs (Winer, 1971). There was a borderline significant difference between the ranks for the conditions, $X^2(3) = 7.762$, $p = .051$. Subjects ranked the thermal blanket task with force reflection to be easiest (1.625), followed by the thermal blanket without force reflection (2.125), then the dual-peg with force reflection (2.875), with the hardest task being the dual-peg without force reflection (3.25). The comments given by the subjects when completing their questionnaires indicated that subjectively they experienced more discomfort in more areas of their bodies (e.g., wrist, shoulder, forearms, fingers) during the force conditions than the non-force conditions for which primarily they experienced soreness in the wrist.

DISCUSSION

The primary hypothesis that was of interest before conducting this experiment was that performance and subjective workload of two tasks would be significantly different when done by a Kraft hand controller in position mode with force reflection than when done without force reflection. This hypothesis was not accepted on the basis of the analyzed results. However, although force reflection tended to create longer average total task completion times (see figure 1) and to be related to somewhat more bodily discomfort, the subjects ranked the force reflection conditions as being easier to perform than the no-force conditions. And, although some overlap occurred in the factor analyses results, more task load was indicated for the dual-peg task than for the blanket task, which corresponds to the subjective rankings of higher difficulty for the dual-peg task.

Interestingly, the increased difficulty or greater factor weight for task load was not reflected in the mental workload ratings or in the Task Load Index measures, e.g., no significant differences were found between these tasks for either mental workload ratings or the Task Load Index. In the ROIL study, the mental workload rating for the thermal blanket task with force reflection was significantly higher than for the no-force condition, but there was no difference for the dual-peg task. The current study agreed with ROIL and Merriken and Brown (1991) in that no difference between the mental workload ratings or the Task Load Index measures, respectively, were found. Das et al., (1991) found that subjects preferred force reflection over none for performing the screw removal, as was found in the current study within tasks.

Previous studies have been inconclusive about force reflection for position control in terms of task completion time. Hannaford et al. (1989) did not find much difference between task completion time for a velcro blocks task, although they did find that force reflection reduced the task completion time somewhat for a single peg-in-hole task. Das et al., (1991) also found a similar difference between no-force and force reflection for a screw removal/insertion task. Stuart et al. (1991) in the ROIL study found that the shortest total task completion times for three tasks were for the Kraft hand controller in position mode with force reflection using the Kraft manipulator system. No differences were found for the other position hand controllers using a different system. Merriken and Brown (1991) found no significant differences for task completion time for a single peg-in-hole task or for an ORU replacement task between position alone and position with force reflection. The latter agrees with the current study, although there was a nonsignificant trend for longer task times with force reflection. Furthermore, that the task performance differed by gender is a very interesting finding from the present study. This difference has not been previously reported and should also be investigated further. It may have implications upon training or selection of telerobot operators.

Reasons for the differences between the results of these studies may include the use of subjects who had various types of experience in the ROIL study versus inexperienced subjects in the current study. Recall that practice was given in the current study until all subjects reached a predetermined performance criteria. This practice was not provided to the subjects in the ROIL study in which only one practice trial was given. Furthermore, the tasks although similar were modified in the current study in an attempt to be more force sensitive and realistic. However, neither the completion time results nor subjective workload ratings reflected that force sensitivity.

CONCLUSIONS

Data trends in the present study tended to indicate an increase in total task time due to force reflection, but this was not statistically significant so that no conclusive statements about force reflection can be made on the basis of the total task time data. However, future work will involve analysis of the subtask data, which may show an effect for force reflection or help explain the gender difference found in this study. The subjective measures used in this study were not consistent with respect to force reflection differences and will require further study. Decisions made based upon such data should be done with caution until such studies occur.

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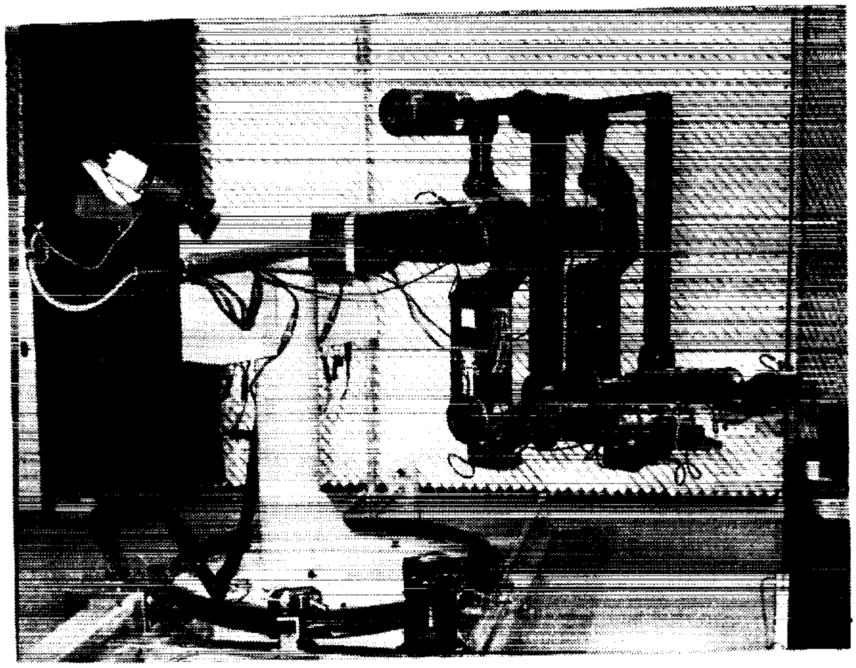

Figure 1. Laboratory Telerobotic Manipulator.

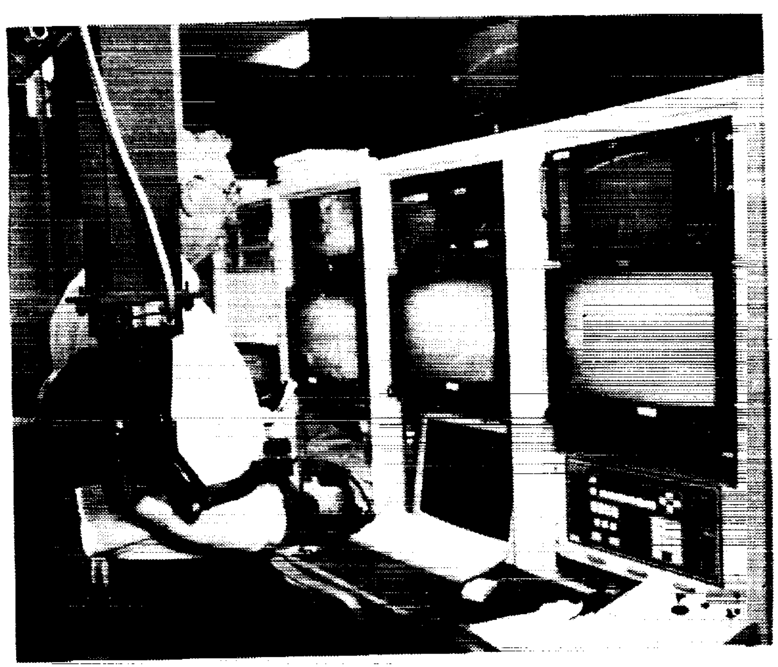

Figure 2. Kraft hand controller and control station.

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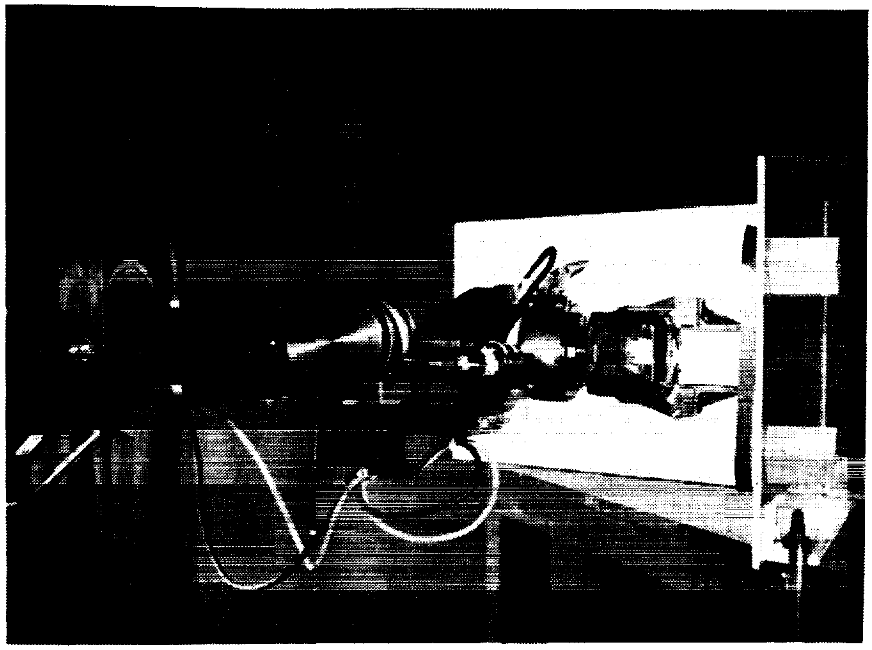
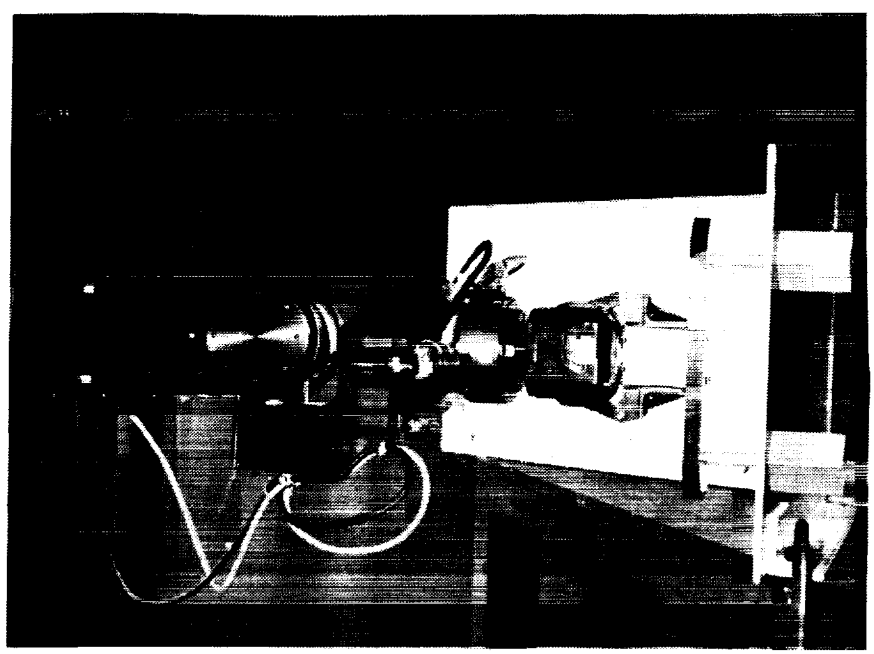


(a) Grasp handle of task-piece.



(b) Extract task-piece.

Figure 3. Four sub-tasks of the dual-peg task.

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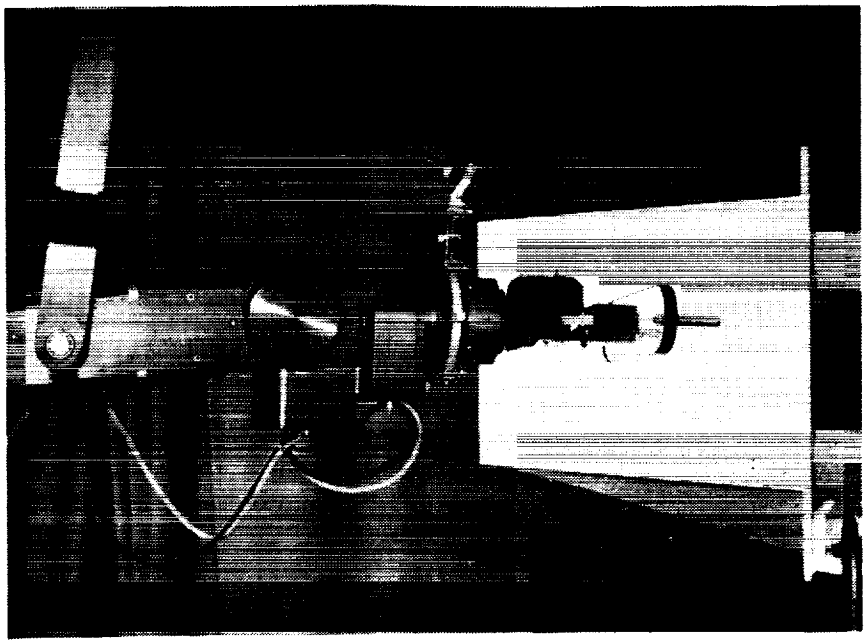
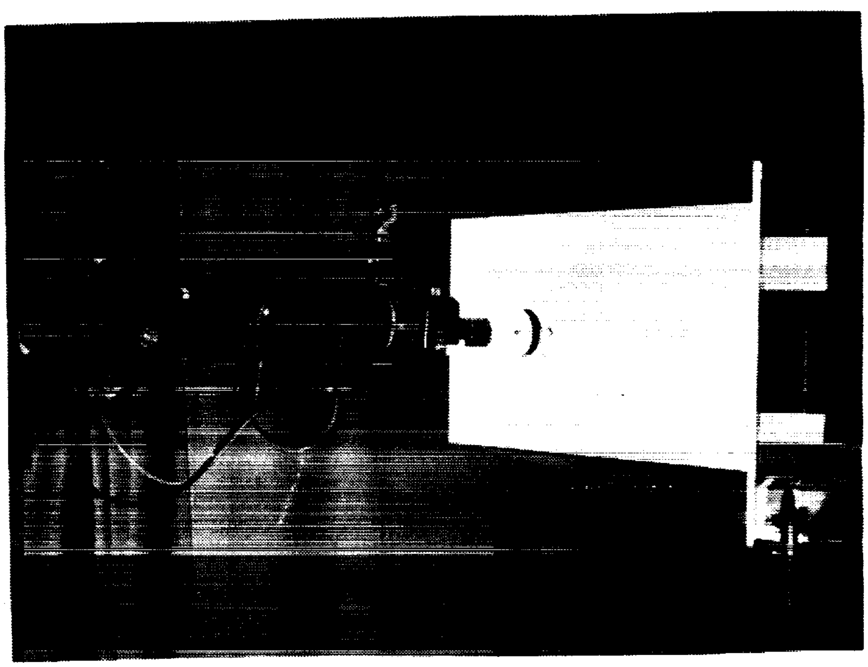
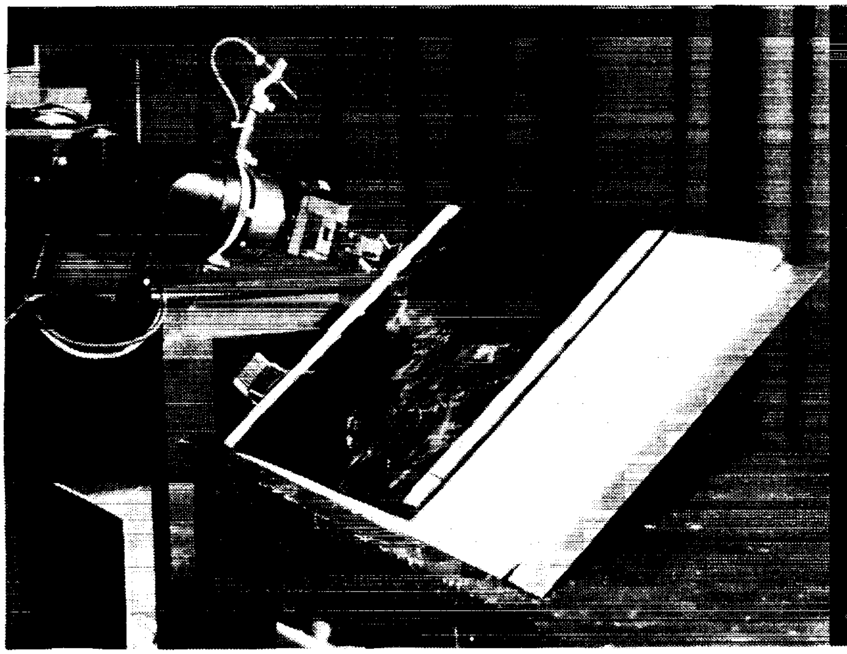


(c) Translate and rotate task-piece.

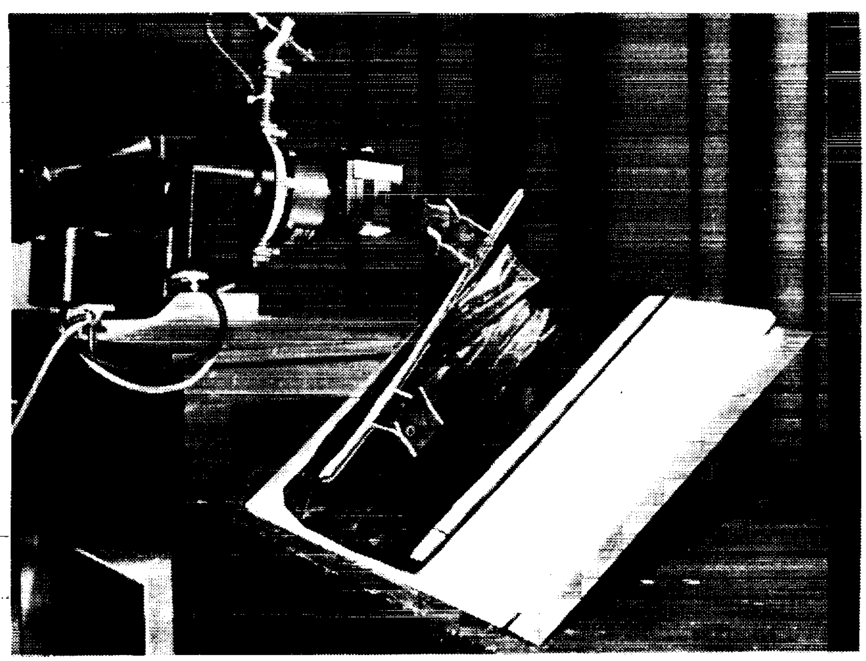


(d) Insert task-piece.

Figure 3. Continued.

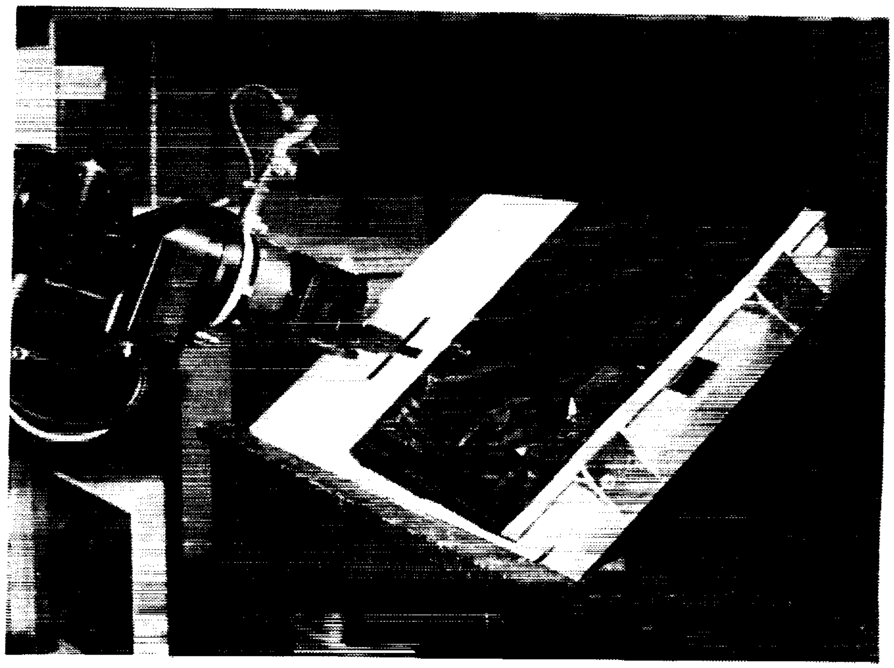


(a) Grasp blanket tab.

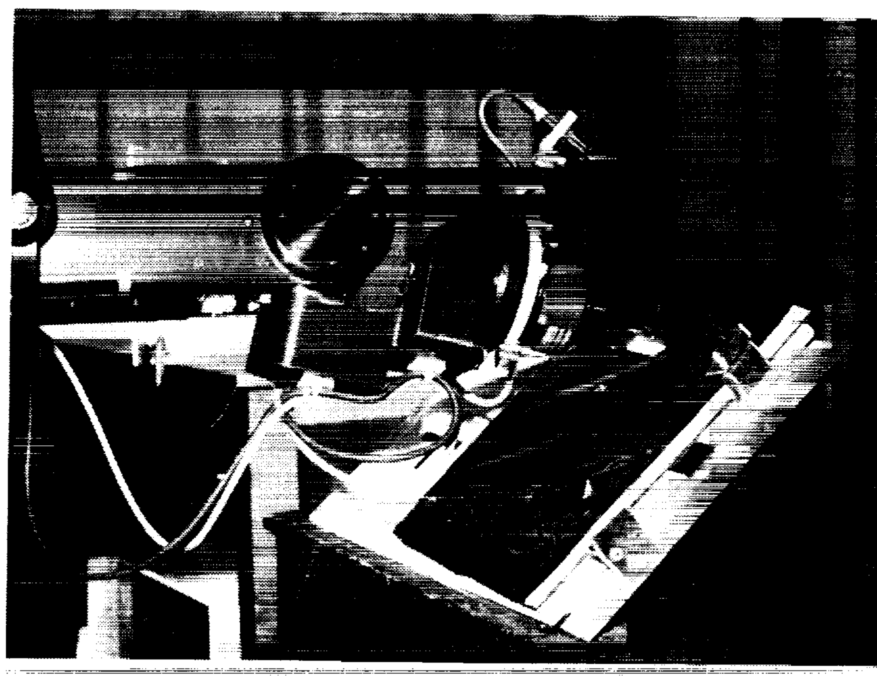


(b) Peel and attach blanket.

Figure 4. Four sub-tasks of the thermal blanket task.



(c) Touch target and translate end-effector.



(d) Grasp blanket tab and reattach blanket.

Figure 4. Continued.

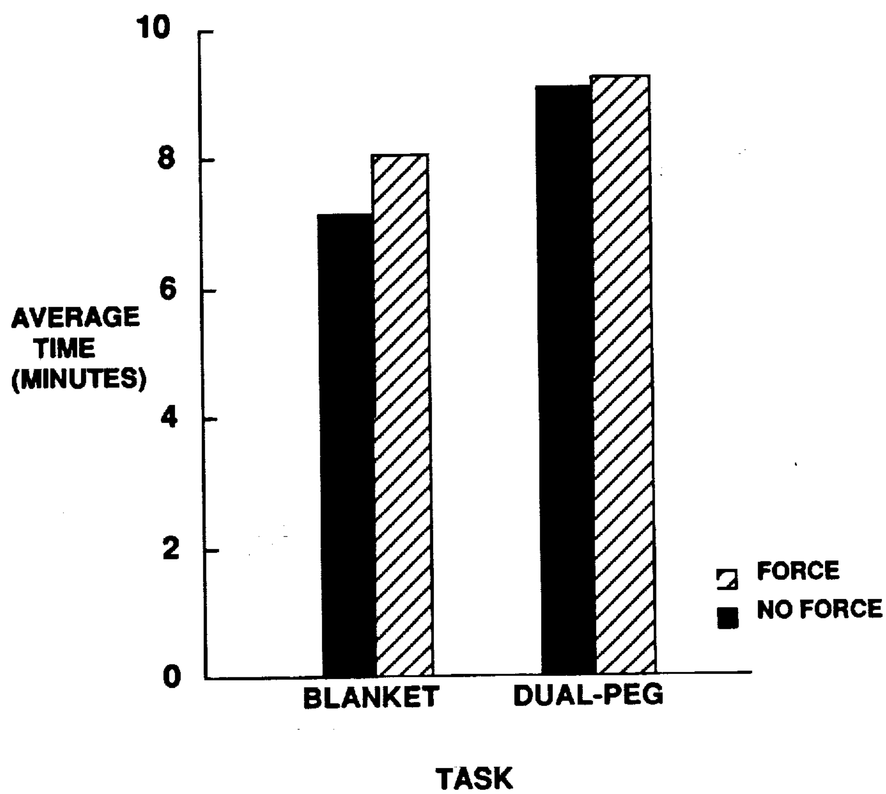


Figure 5. Task completion times for force reflection and no force reflection conditions (no significant differences).

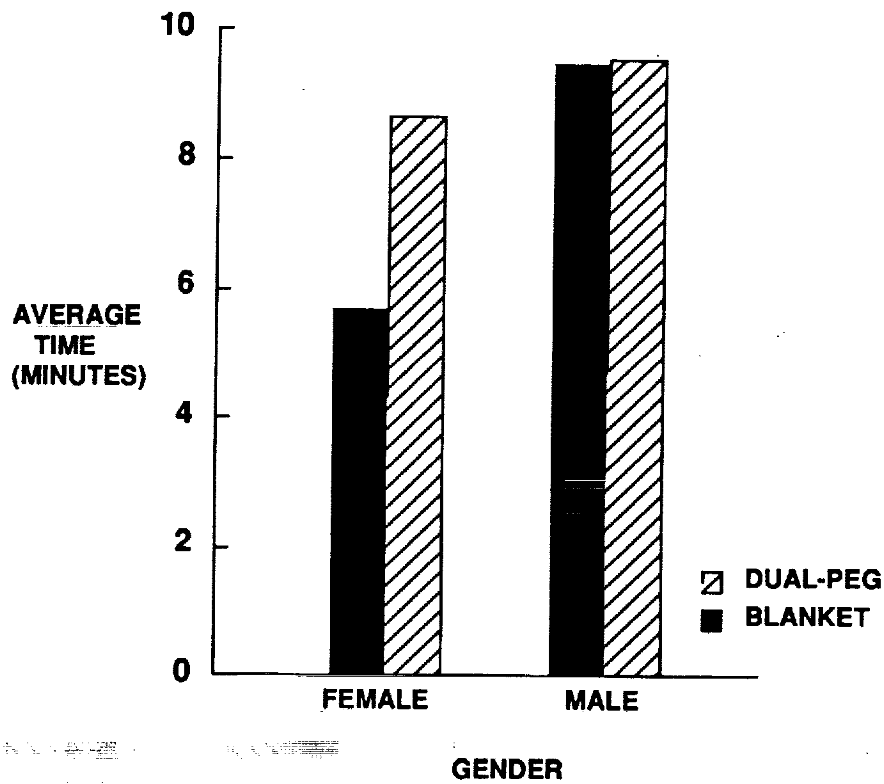


Figure 6. Effect of gender on task performance times.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
March 1992

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Telerobotic Hand Controller Study of Force Reflection with Position Control Mode

5. FUNDING NUMBERS
595-11-22

6. AUTHOR(S)
K. F. Willshire, W. W. Hankins, A. T. Morris, and R. W. Mixon

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23665-5225

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
NASA TM-107569

11. SUPPLEMENTARY NOTES
Presented at the Ergonomics Society Annual Conference, April 7-10, 1992, in Birmingham, England.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Unclassified--Unlimited

Subject Category 63

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

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14. SUBJECT TERMS
Telerobotics, Force Reflection, Position Control

15. NUMBER OF PAGES
17

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified		

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18