

MANIPULATOR COMPARATIVE TESTING PROGRAM

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ABSTRACT

The Manipulator Comparative Testing Program examined differences among manipulator systems from the United States and Japan. The manipulator systems included the Meidensha BILARM 83A, the Model M-2 of Central Research Laboratories Division of Sargent Industries (CRL), and the GCA Corporation PaR Systems Model 6000. The site of testing was the Remote Operations Maintenance Demonstration (ROMD) facility, operated by the Fuel Recycle Division in the Consolidated Fuel Reprocessing Program at the Oak Ridge National Laboratory (ORNL).

In all stages of testing, operators using the CRL Model M-2 manipulator had consistently lower times to completion and error rates than they did using other machines. Performance was second best with the Meidensha BILARM 83A in master-slave mode. Performance with the BILARM in switchbox mode and the PaR 6000 manipulator was approximately equivalent in terms of criteria recorded in testing. These data show no impact of force reflection on task performance.

INTRODUCTION

The Manipulator Comparative Testing Program compared the performance of selected manipulator systems under typical remote-handling conditions. The program was jointly sponsored by Martin Marietta Energy Systems, Inc., (for the U.S. Department of Energy) and by the Power Reactor and Nuclear Fuel Development Corporation (PNC) (for

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Japan). The site of testing was the ROMD facility, operated by the Fuel Recycle Division of the ORNL. The manipulator systems compared were the Meidensha BILARM 83A, the CRL Model M-2, and the GCA Corporation PaR Systems Model 6000. Six manipulator and control mode combinations were evaluated: (1) the BILARM in master-slave mode without force reflection, (2) the BILARM in master-slave mode with force reflection, (3) the Model M-2 in master-slave mode without force reflection, (4) the Model M-2 in master-slave mode with force reflection, (5) the BILARM with switchbox controls, and (6) the PaR 6000 with switchbox controls.

METHOD

Manipulator Systems

Meidensha BILARM 83A. The Meidensha BILARM 83A is a force-reflecting master arm-controlled electromechanical manipulator system. It is unique in that the slave arm can also be operated as a switchbox-controlled manipulator (with no force feedback), using a position-control switchbox. The slave arm has a handling capacity of 25 kg in any position and 8 degrees of freedom (including the gripper).

The BILARM 83A slave arm joints are each driven by a packaged drive unit consisting of a permanent-magnet dc motor, planetary gear drive and harmonic gear drive in series, and a plastic film potentiometer for position signals. Torque at the slave arm is measured at each of three joints by a load cell, which is located to minimize friction losses. This force signal is used as a drive signal for the three force-reflecting master joints and as local feedback to the slave. Force-reflection ratios (the ratio of force applied at the slave to force output at the master arm) from 1:1 to 9:1 are available, as is a no-force-reflection setting. The switchbox control is unique in that it uses position controls instead of the usual rate controls applied to these types of devices. The potentiometers on the BILARM 83A switchbox directly control slave joint positions rather than joint velocity.

CRL Model M-2. The CRL Model M-2 manipulator is a bilateral, force-reflecting servomanipulator system. The master arms are 7 degrees of freedom (including the gripper), kinematic-replica controllers. The slave arms each have a handling capacity of 23 kg, continuous in any position. The kinematics are in the typical "elbows-up" stance used by all commercially available servomanipulators in the United States and Europe.

The M-2 slave joints are each driven by a brushless dc servomotor with integral-position and velocity encoding. The output of the upper 3 degrees of freedom are gear and lever driven. The lower 4 degrees of freedom of master and slave are cable driven. The lower master-controller degrees of freedom are tape driven. A standard position-position technique, implemented in digital control hardware, provides force reflection. Force-reflection ratios from 1:1 to 8:1 are available, as is a no-force-reflection setting.

GCA Corporation PaR Model 6000. The PaR Model 6000 is a rate-controlled power manipulator. The controller provides rate control of each joint of the slave arm, which has 181-kg capacity in all positions and 7 degrees of freedom (including the gripper). The slave arm uses permanent-magnet dc motors with continuously variable-speed control.

Research Design

The Comparative Testing Program included three interrelated experiments: the strategy of testing was to begin with very simple tasks and was to include progressively more realistic tasks and conditions as the testing progressed. In Experiment 1, five operators repeatedly completed a set of three simple tasks, using each of the manipulator systems. Criteria of performance included the time required to complete each task and the number of errors committed during completion of each task. Errors were recorded by an observer during task completion and included misalignments of pieces to be joined, misses during attempts to grasp or insert objects, drops, system overloads, and damage to the manipulator or task hardware. The results of the first experiment guided the development of a testing plan for Experiment 2. A slightly more complex set of tasks was used and, as in Experiment 1, the performance criteria included time to completion. However, the error measurement was expanded to include separate tallying of 18 types of critical incidents, events which are important to the operators' performances. These included not only errors but also other important occurrences such as using two hands to control one manipulator arm, misaligning items to be connected, grasped items slipping within the tongs, etc. The operators also rated the manipulators by completing a simple questionnaire in Experiment 2. In Experiment 3, operators did a single, realistic task under conditions designed to simulate those that would be encountered in remote maintenance. The criteria of performance were task completion time and the total of all critical incidents.

Statistical Procedures

The general strategy of analysis was to compare averages of the criteria among the six combinations of manipulator and mode. The computational procedures were derived from O'Brien and Kaiser¹ and specifically designed for the situation in which each of a set of operators was tested under all of the combinations of machine and mode of control. The statistical analyses incorporated a specially adapted version of analysis of variance (ANOVA) in which each comparison was based on a separate contrast between averages of the dependant measures calculated for two or more of the experimental conditions. For example, in comparing the BILARM with the M-2 on time to completion of the impact-wrench task, the average of each operator's scores from sessions involving the BILARM was contrasted with his average from sessions involving the M-2. The average of the differences for the operator group was tested for significance using a dependant t-test² with n-1 degrees of freedom, where n was the number of operators. A t-test was considered significant if it exceeded the criterion value of t at

$\alpha < 0.05$. In this paper, significant results will be reported, but the details of the statistical tests will not be reported due to space limitations. Complete details of the statistical tests are available in ref. 3.

EXPERIMENT 1

Operators

Five operators participated in Experiment 1. Four were male employees of Martin Marietta Energy Systems who were working at ORNL at the time of the Comparative Testing Program. One was a male employee of PNC. All the ORNL operators were experienced and qualified (according to procedures established by the Fuel Recycle Division for operators of remote-handling equipment) manipulator operators. None of the ORNL operators had fewer than 18 months of experience with manipulators. Before beginning the testing trials in Experiment 1, each of the four ORNL operators was given 1 h of practice on the M-2 manipulator and 3 h of practice on the BILARM with master-slave controls. Each was also given 1 h of practice with each of the two switchbox combinations before the trials involving switchbox controls. The operator who was an employee of PNC was relatively less experienced with the M-2 and relatively more experienced with the BILARM. He was given 3 h of practice with the M-2.

Tasks

The three tasks selected for Experiment 1 were designed to be representative of remote-handling task primitives for fuel recycle facilities and other remote-handling applications. They were also designed to be easily performed with each of the combinations of machine and mode of control, and they could be completed several times in a 1-h session. The tasks included dismounting and mounting a remotely adapted electrical motor, inserting a cylindrical peg into a hole, and engaging a bolt with an impact wrench.

Each operator completed two sessions of trials under each of the six combinations of manipulator and control mode. A session consisted of five repetitions of each of the three tasks.

Results

Figure 1 shows the averages of time and errors per task repetition for each manipulator and control mode in Experiment 1. These results were consistent for the operators from the United States and the PNC operators. Operators using the M-2 performed the tasks significantly faster than they did with the other systems. The M-2 yielded fewer errors for each task, although the difference was only significant on the peg-in-hole task. There were no significant differences between force-reflection and no-force-reflection conditions for time to completion or for the number of errors committed per trial in Experiment 1. The BILARM was significantly faster in master-slave mode than in

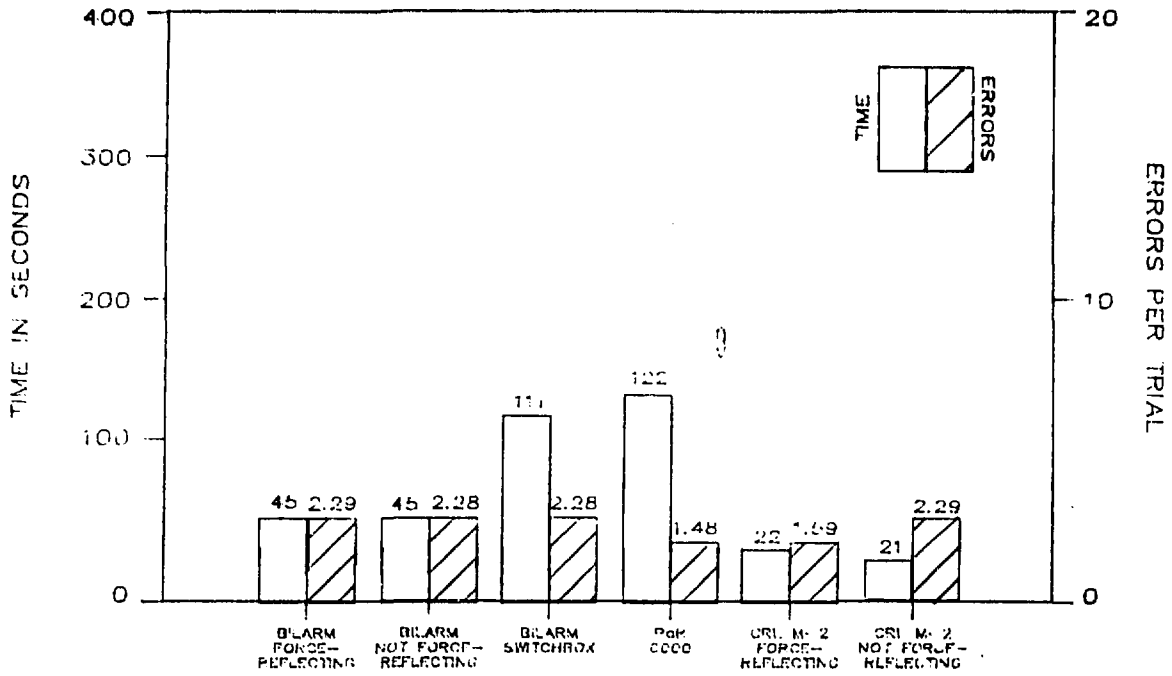


Fig. 1. Averages of time and errors, Experiment 1.

switchbox mode. Surprisingly, on the peg-in-hole task, operators using the master-slave mode committed significantly more errors than they did using the switchbox mode, although there were no differences on the other tasks. When averaged across all three tasks, operators using the BILARM completed tasks in significantly less time than they did when using the PaR arm. For errors, there was a significant difference between these machines on the peg-in-hole task, with fewer errors committed by operators using the PaR arm.

EXPERIMENT 2

Operators

Four operators participated in Experiment 2. Three of the four were part of the group from Experiment 1. The fourth operator had worked 5 years as a part-time operator of remote manipulator systems. Each operator completed 18 testing sessions. Each session consisted of two repetitions of each of two tasks. The series of 18 sessions was organized as four blocks of four sessions, followed by one session in the BILARM switchbox combination and one session in the PaR switchbox combination. To balance practice effects, within each block every operator completed all four of the master-slave combinations (BILARM force-reflecting, BILARM nonforce-reflecting, M-2 force-reflecting, M-2 nonforce-reflecting). In each of the four blocks, the four master-slave combinations were arranged in a different order. This testing sequence was specially designed to equalize the effects of transferring from one combination into another. Each operator's sequence of 16 sessions of master-slave combinations included all of the possible types of changes from one condition into another. For instance, the change from the M-2 with force reflection to the BILARM with force reflection was one of 12 possible changes. The opposite change (from the BILARM with force reflection to the M-2 with force reflection) was another.

Tasks

The three tasks selected for Experiment 2 were designed to be representative of remote-handling task primitives for recycle facilities and other general remote-handling applications. They were also designed to be easily completed with each of the combinations of manipulator and control mode. Each was simple enough to be completed several times in a 1-h testing session. The tasks were designed to be somewhat more difficult than the tasks used in Experiment 1. The tasks included a modified version of the peg-in-hole task from Experiment 1 (tolerances were reduced to make insertion more difficult), threading a bolt into a nut, and tubing-connector replacement (tubing connectors were held in place by TRU connectors).

Results

Figure 2 shows the averages of time and total critical incidents per task repetition in Experiment 2 for each manipulator and control-mode combination. For all three tasks, operators using the BILARM

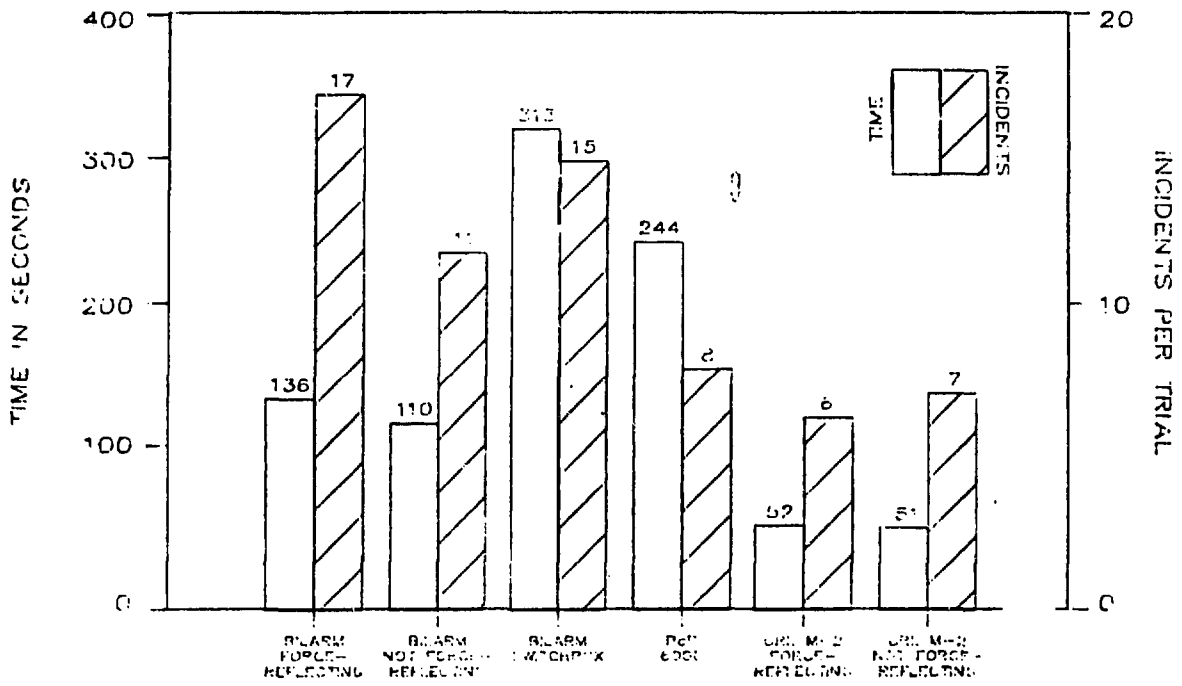


Fig. 2. Averages of time and total incidents, Experiment 2.

required significantly longer to complete tasks than did operators using the M-2. The number of critical incidents was significantly greater for the BILARM than for the M-2 for the average of the three tasks and within each task. For all tasks, critical incidents which showed significant differences between machines occurred more frequently on the BILARM than on the M-2. Operators rated the BILARM significantly higher than the M-2 on the task difficulty questionnaire. In general, the BILARM performance was better under the nonforce-reflection condition. In contrast, for the M-2 there was no consistent difference in performance between force-reflection and nonforce-reflection operation.

The analysis of control-mode differences (master-slave versus switchbox control) within the BILARM concentrated on the task-completion-time variable. Critical incidents occurred very rarely in trials involving switchbox-controlled manipulators. The critical incidents were deemed too unreliable for use in analysis of these systems. Operators using the switchbox controls required more time to complete tasks than they did when using master-slave controls for each task. Analysis of differences between switchbox-controlled systems also concentrated on task-completion time. There was a significant difference between operators' averages on the PaR arm and on the BILARM. However, examination of the within-task averages suggests that the difference between the two machines is related to the way the machines reacted to a specific characteristic of the bolt-threading task. The bolt-threading task favored the PaR arm because it has continuous wrist roll. With the PaR arm, operators were able to extend the wrist along a straight line and then rotate the wrist continuously. Rotation of the BILARM was limited to $\pm 115^\circ$; therefore, operators using the BILARM had to tighten the bolt with a series of ratcheting motions. On tasks which were not dependant on this one motion for performance, there was no difference between the switchbox-controlled manipulators.

EXPERIMENT 3

Operators

The four operators who participated in Experiment 3 were the same as the group from Experiment 2. In Experiment 3, machine-mode combinations were assigned orders in the same way that sequences were assigned in Experiment 1. Each operator completed one session with each machine-mode combination. Procedures were the same as for Experiment 2, except that operators were allowed to complete as many repetitions of the task as they could (up to a limit of three repetitions) in a 1-h testing session. The dependant measures recorded for this experiment were the same as for Experiment 2.

Task

The task used in Experiment 3 was a mock-up of an instrument package that might be encountered in the maintenance of a fuel recycling facility. It consisted of a square, steel framework attached to the horizontal surface of the test stand by two captive fasteners. A tubing

jumper was connected to the top of the framework by a TRU connector, and another TRU connector attached the jumper to the surface of the test stand. An electrical connector was attached to the top of the framework and to the vertical surface of the test stand. This task was selected to represent a typical full-component replacement-type operation.

Results

Figure 3 shows the averages of time and total critical incidents per task repetition in Experiment 3 for each manipulator and mode combination. Operators using the M-2 manipulator completed the task in significantly less time than when using the BILARM. Operators using the M-2 committed significantly fewer critical incidents per trial. There was no effect of the force-reflection conditions on task completion time or total critical incidents in Experiment 3. The failure to find a statistically significant difference is due to the difference in the way operators responded to force reflection on this task. Two of the operators completed the task in slightly less time with force reflection, while two other operators took considerably longer with force reflection. The difference in averages reflects the large performance decrement in the force-reflection condition for the latter pair of operators.

Operators completed the task in significantly less time when using the master-slave mode than they did when using the switchbox controller. There was no difference between the two switchbox-controlled manipulators in the average time required to complete the task. Operators using the BILARM committed significantly more critical incidents per trial than operators using the PaR manipulator.

DISCUSSION

Summary of Findings

In all the stages of testing, the CRL Model M-2 manipulator had consistently lower times to completion than any other machine. The Meidensha BILARM 83A, operating in master-slave mode, was the second fastest machine (although occasionally it fared no better than either of the switchbox-controlled systems). The BILARM, in switchbox mode, and the PaR 600 manipulator were approximately equivalent in terms of the performance variables recorded in the testing. The number of errors and critical incidents reflected the same trends, although the differences between conditions were smaller. This suggests that this type of measure is a less sensitive criterion for the comparison among manipulator systems.

The effect of force reflection differed between manipulators: it adversely affected performance of all tasks with the BILARM, but generally had the opposite effect for the M-2 (although the differences were not significant with the M-2). This reflects the lower fidelity and poorer kinematic arrangement for force reflection on the BILARM. For this machine, force-reflection operation resulted in resistance to

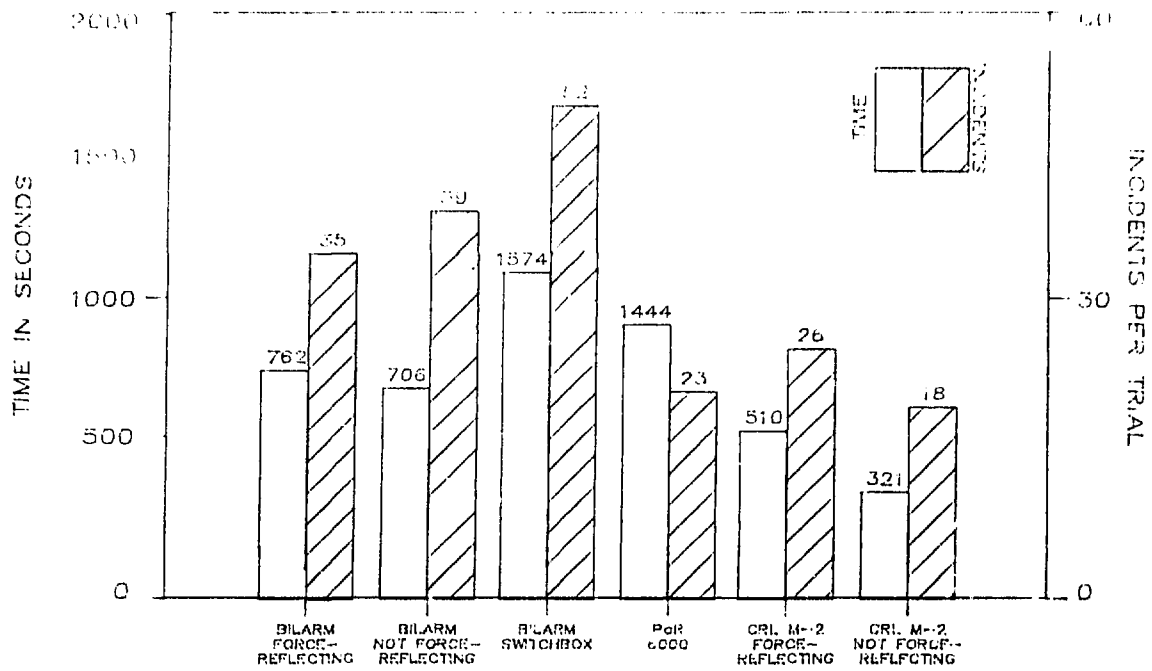


Fig. 3. Averages of time and total incidents, Experiment 3.

master-control motions and failed to provide force information on a vertical axis (perpendicular to the yaw axis). These effects combined to make the BILARM a much less effective machine when its force reflection was engaged. The M-2, on the other hand, generally suffered no performance decrement with force reflection. Operators were able to complete tasks with fewer occurrences of some critical incidents with force reflection than without it. However, for the tasks used in this testing, the differences were not statistically significant. This should not be interpreted as evidence that force reflection is not beneficial in remote handling. These experiments failed to address the question of force reflection in a definitive fashion. The dependant measures collected were incomplete in terms of assessing the impact of force reflection, since the forces applied to task components were not measured. The testing program was designed to assess the strengths and weaknesses of the various manipulator systems included, which represent a fairly wide range of types of systems, from power manipulators to dexterous servomanipulators. To test this wide range of manipulators, it was necessary to restrict the range of tasks and conditions included. The goals, conditions, and tasks of the testing program combined to make these data inadequate for making a final judgment on the efficiency of force reflection in remote handling.

The Manipulator Comparative Testing Program contributed to the mission of the Fuel Recycle Division of ORNL and to the mission of PNC by demonstrating differences between remote-handling systems, by making a preliminary investigation into the effects of force reflection on remote-handling performance, and by providing a venue for the development and testing of methods for evaluating manipulator performance.

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