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# Test Results: The Manipulator Operator Skill Test

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CONSOLIDATED FUEL REPROCESSING PROGRAM



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## ABSTRACT

The Manipulator Operator Skill Test (MOST) was developed to measure important servomanipulator operator skills. The MOST is based on careful analysis of servomanipulator motions and prototypical remote maintenance tasks. It has been validated with servomanipulator operators from the Oak Ridge National Laboratory (ORNL). This report details the development of the MOST and describes testing carried out with it.

Skill test development followed a three-stage strategy. First, a list of job elements deemed important to performance of remote handling tasks was generated. Next, this list was culled for skills which seemed particularly important for maintenance of process-type equipment that will be found in future nuclear reprocessing facilities. Finally, a task was designed that measured key skills, and a procedure for performing the task was developed.

The predictive validity of the skill test has been assessed at ORNL. Ten servomanipulator operators participated in a study to determine how well performance of the skill test predicts performance of a realistic remote maintenance task. Multiple linear regression found that the time required to complete the skill test is an effective predictor of realistic task completion time. The multiple $R$ for the predictive equation was 0.97.

## 1. INTRODUCTION

The Oak Ridge National Laboratory (ORNL) in the United States and Tokai Works of the Power Reactor and Nuclear Fuel Development Corporation (PNC) of Japan are cooperating in performance testing of several advanced servomanipulator systems. The testing program features identical test stands installed in the two countries. Japanese operators will use Japanese manipulators to complete tasks on the test stand, and U.S. operators will use U.S. manipulators to complete the same tasks using identical test instructions and tools. Because different sets of operators will use the manipulator systems in the two countries, comparisons of manipulators will be affected by differences in operator groups. This mixing of the effects of two potential sources of performance differences is called confounding.

While it will not be possible to completely separate operator and manipulator effects, there are two methods for improving the accuracy of manipulator comparisons. First, operators in each country may be selected to equate the skill levels of the two groups. One way of doing this is to match operators on a one-to-one basis; each operator in the United States will have a counterpart in Japan with about the same skill level. Manipulator comparisons will be based on the differences within matched operator pairs.

Statistical adjustment of performance is a second method for dealing with the operator-manipulator confounding. A set of procedures called Analysis of Covariance (ANCOVA) exists for this purpose. ANCOVA would use a measure of skill to predict what each operator's performance on the test stand tasks should be. Systematic deviations from predictions would be attributable to manipulator differences. In other words, ANCOVA would perform an analysis of residuals from performance predicted by skill test scores. Consistent differences between groups defined by manipulator would be evidence of manipulator differences.

For either method of accounting for operator differences, an accurate measure of operator skill is necessary. This report describes the development of a skill test and a testing program carried out to determine the validity of the skill test.

## 2. SKILL TEST DEVELOPMENT

This section describes the process of skill test development, which followed a three-stage strategy. First, a list of job elements deemed important to performance of remote handling tasks was generated; next, this list was culled for skills that seemed particularly important for tasks on the Manipulator Test-Test Stand; and finally, a task measuring the key skills was designed, and a procedure for performing the task was developed.

### 2.1 IDENTIFICATION OF IMPORTANT SKILLS

Skill is the ability to perform a task; performance of a complex task is determined by the operator's skill level on the subtasks that compose the larger task. Therefore, performance on a complex task may be predicted by evaluating skill on generic subtasks. For the Manipulator Operator Skill Test (MOST), skill identification began with development of a list of job elements for remote manipulation. Job elements are the fundamental subtasks to which remote maintenance tasks may be reduced. These were developed from the fundamental motions of work developed for analysis of manual tasks.[1] Experienced manipulator operators and observers of manipulator operations examined the list and assisted in refining the job elements. Table 1 is the final list of job elements.

Three job elements seemed particularly important for performance of remote maintenance tasks requiring dexterity: (1) spatial orientation, (2) positioning, and (3) assemble-insert.

### 2.2 THE SKILL-TEST TASK

The task selected for the MOST is a variation on Fitts' tapping task.[2] The classical Fitts task requires motion along a straight path from a starting point to position an object on a target, followed by a return to the starting point. The rate of motion is related to the information-processing capacity of the performer. The skill-test task modifications include (1) a three-dimensional path requiring changes in the spatial orientation of a stylus in the grasp of the manipulator, (2) insertion of the stylus into targets located on the motion path, and (3) three targets instead of two. The modifications ensure that operators must adapt to changing spatial orientations of the targets, position the stylus accurately, and assemble the stylus and target by making an accurate insertion.

### 2.3 MOST TASK BOARD

Figure 1 is a photograph of the MOST task board. The board consists of two pieces of aluminum sheet fastened together at right angles. Three task stations are attached to the board. One

Table 1. Manipulator job elements

| | |
|---|---|
| 1. Plan | Occurs when the operator develops a strategy for doing a task or stops to decide what the next step should be |
| 2. Spatial orientation | Development of an internalized representation of the location of objects (including the manipulator) in the remote area. Important for interpreting the relationship of motion inputs to the manipulator and responses as displayed on televised views of the remote area |
| 3. Visual search | Attempt to locate something using the remote viewing system |
| 4. Tactile search | Attempt to locate something by feeling for it with the manipulator. Only possible with force feedback |
| 5. Select | Choosing an item (wrench, bolt, etc.) from an array of items |
| 6. Grasp | Closing a tong around an object and securing it in the grip of the tong or otherwise securing an object to the end-effector of a manipulator |
| 7. Move | Transporting a grasped object from point to point within the remote area |
| 8. Hold | Securing an object in position while performing an operation on it |
| 9. Release | Terminate a grasp |
| 10. Position | Placing an object in a position necessary for completion of the task |
| 11. Turn | Moving the tong in a circular path as when using a wrench |
| 12. Assemble-insert | Inserting an object into another |
| 13. Assemble-thread | Same as for assemble-insert, except that the two items are threaded and must be screwed together |
| 14. Disassembly | Taking connected objects apart; includes disassembly of objects that are threaded |
| 15. Check/inspect | Checking the quality of work completed or attempting to locate failed components or flaws in objects |

station is mounted on the vertical member of the task board with a vertical target surface. The angle of the vertical surface relative to the horizontal member of the task board is adjustable. Two other stations are mounted on the horizontal surface of the board; these stations have horizontal target surfaces. The distance from the vertical plate is adjustable for each of these stations. The target plate can be rotated through 360°; thus, it is adjustable for all three stations.

A two-prong stylus is provided for insertion into the holes in each station's target. During testing, the stylus is held in the end-effector of the manipulator and inserted into the target at each station in turn. Figure 2 is a photograph of the stylus in the grasp of a manipulator end-effector. Proper insertion causes the rings scribed around the prongs of the stylus to pass beneath the surface of the station target. The tolerance of the stylus and target holes was machined to 1/32 in.

ORNL–PHOTO 4768–86

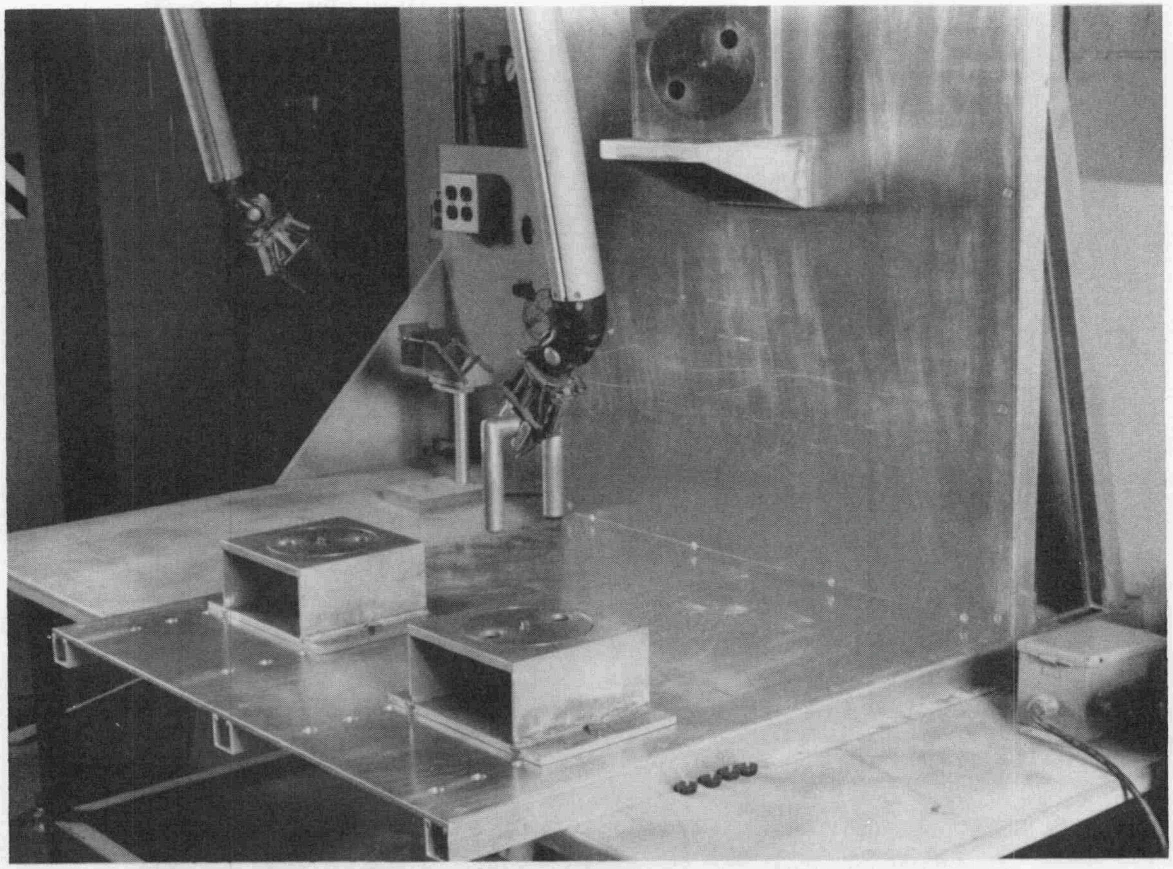

Fig. 1. MOST task board.

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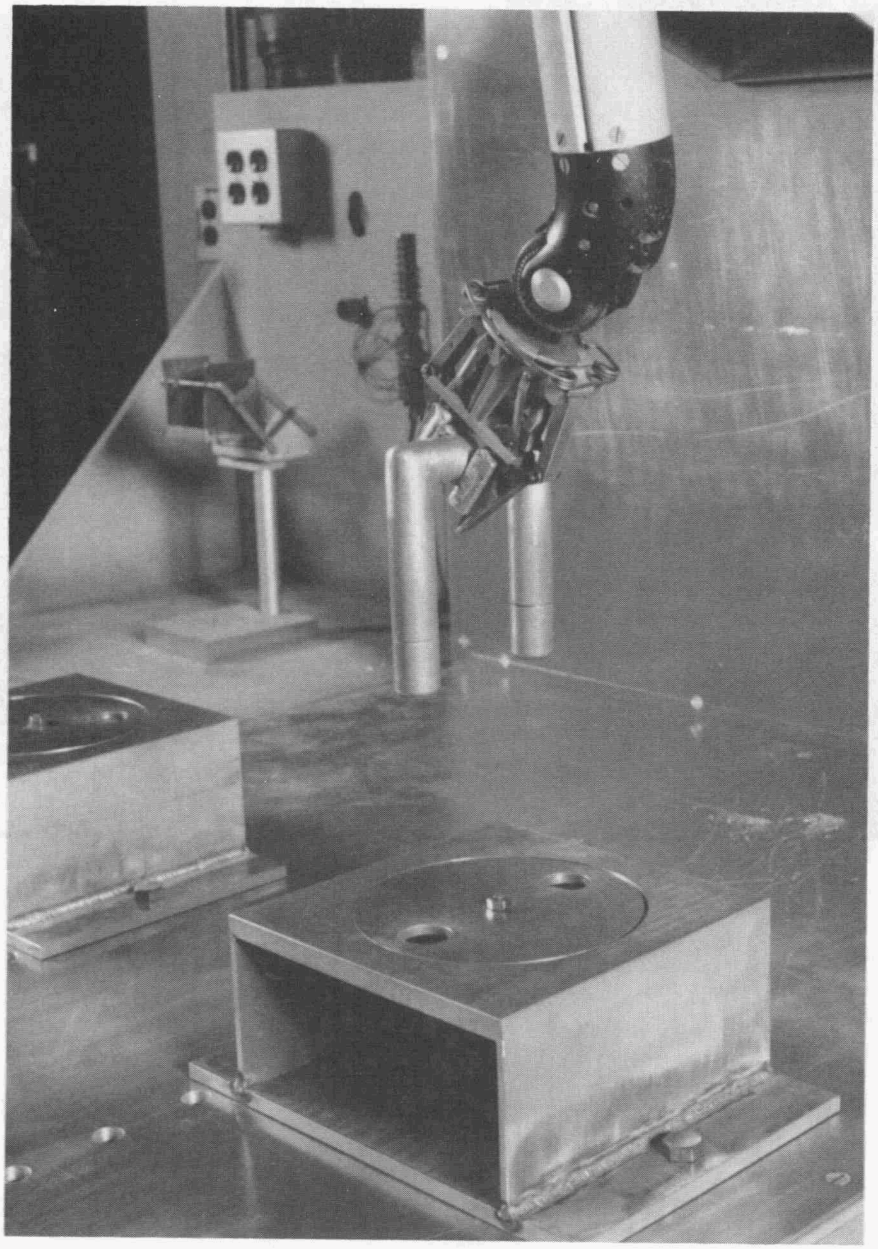

Fig. 2. MOST stylus and manipulator end-effector.

# 3. THE TESTING PROGRAM

This section describes an experiment conducted to see how well scores on the MOST could predict performance of a more realistic remote handling task.

## 3.1 METHOD

### 3.1.1 Subjects

Subjects for the experiment were volunteers from the staff of the ORNL's Fuel Recycle Division (FRD). A total of ten persons participated in the study. Four of the subjects were trained and qualified remote manipulator operators, three were persons who routinely observed the operation of remote handling equipment, and three were complete novices with no experience in operation of remote equipment.

### 3.1.2 Apparatus

The remote handling equipment used in the study included a remote manipulator and a television viewing system. The manipulator used in the study was a Central Research Laboratories' (CRL) Model 8 manipulator. The CRL M-8 is a mechanical master/slave manipulator with a "through-the-wall" configuration.

The television system included one black-and-white television camera linked to a 19-in. (diagonal) back-and-white television monitor. The monitor was positioned between the manipulator master controllers and was directly in front of the position occupied by the operator during testing. A videotape recorder was also linked to the television camera; videotapes of each trial were made during testing.

Figure 3 shows the skill-test task board and the positions the manipulators, television camera, and television monitor occupied during testing. The task board was located so that the first station was directly under the first joint of the manipulator slave. The camera positions were as follows.

**Position 1.** In this position the camera had a line of sight parallel to a line drawn through the sagittal plane of the manipulator pair. In other words, the camera was in a position directly in front of the task board and aimed at the center of the task board.

**Position 2.** In this position the camera was to the right-hand side of the task board (facing the task) and had a line of sight with an angle of 45° between it and a line lying on the sagittal plane of the manipulator pair. In other words, the camera is offset to the right so that its line of sight is 45° to the front edge of the task board.

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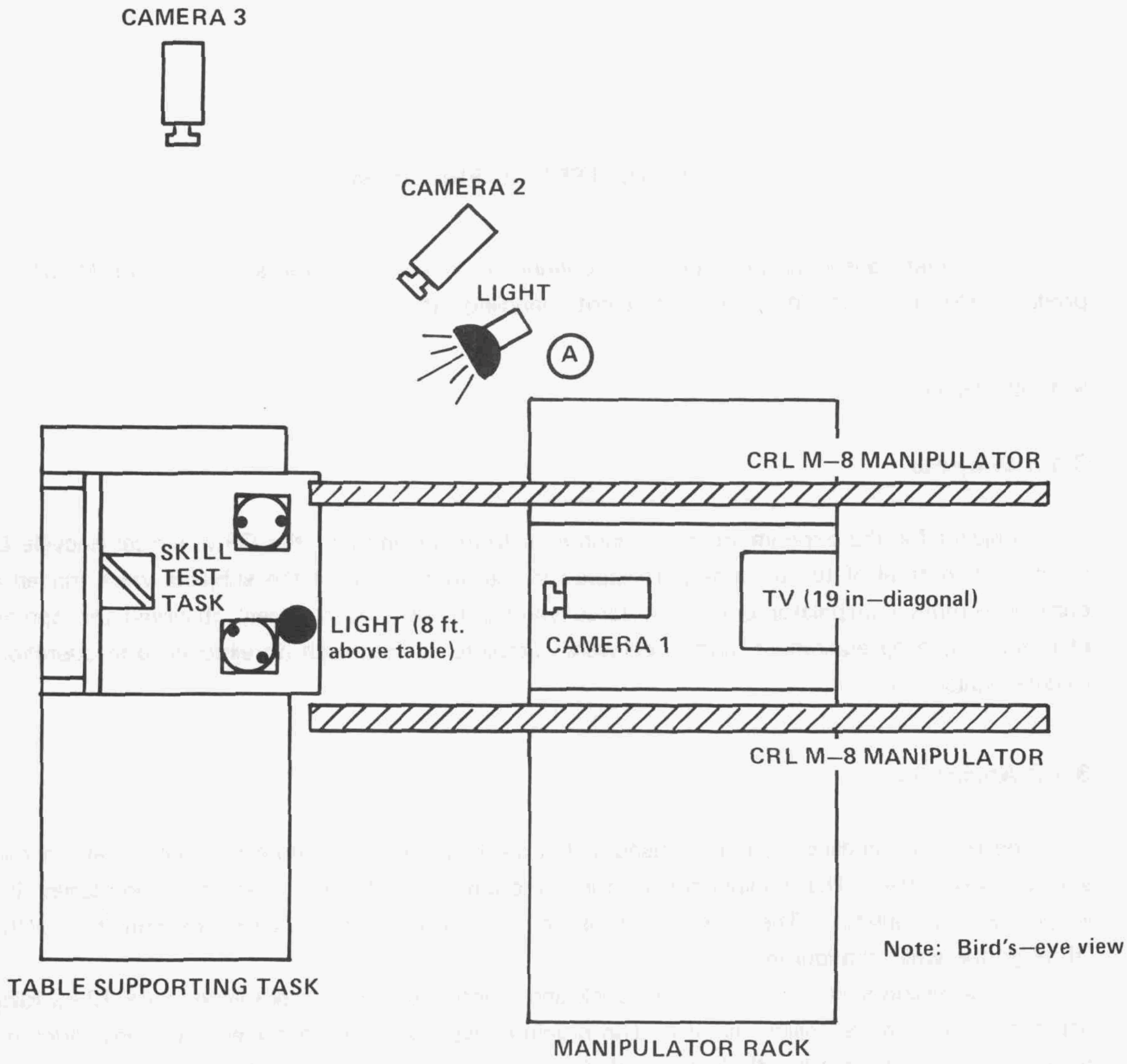


**Fig. 3. Locations of test tank, cameras, lights, and manipulators.**

**Position 3.** In this position the camera was placed to the right-hand side of the task board (facing the task) and had a line of sight with an angle of 90° between it and a line on the sagittal plane of the manipulator pair. In other words, the camera was offset to the right so that its line of sight was parallel to the back edge of the task board.

Lighting was the same for all camera positions. The main light source was set up in position A (see Fig. 3) and aimed at the center of the task board. This provided the basic light for the viewing system. A light located directly over the task board provided fill lighting (low-focus, low-intensity lighting designed to prevent deep shadows). The total illumination was 15 ft c (approximately 162 lx).

### 3.1.3 Criterion Task

This task was a mock-up of an electrical connector replacement task of the type that might be encountered in a nuclear fuel reprocessing plant. Figure 4 is a photograph of the task. Three vertical sheets were welded together at 90° angles to form three sides of a half-cube, with electrical connector sockets mounted on the inside of the cube. Three sockets were mounted on the horizontal base of the cube, two were mounted on the left-hand side, and one was mounted on the right-hand side. The task required operators to pick up four 1.75-in. military connectors (with the threaded rings removed) and plug them into four sockets. The three sockets mounted on vertical sheets and one socket mounted on the horizontal base were used. After inserting all four electrical connectors, the operators removed each from its socket and returned it to the starting position. Figure 4 shows the electrical connectors in their starting positions.

### 3.1.4 Procedure

Operators performed the task ten times with the camera in position 1, five times with the camera in position 2, and five times with the camera in position 3. After completing the five repetitions at position 3, the camera was returned to position 1, and the operators completed the task

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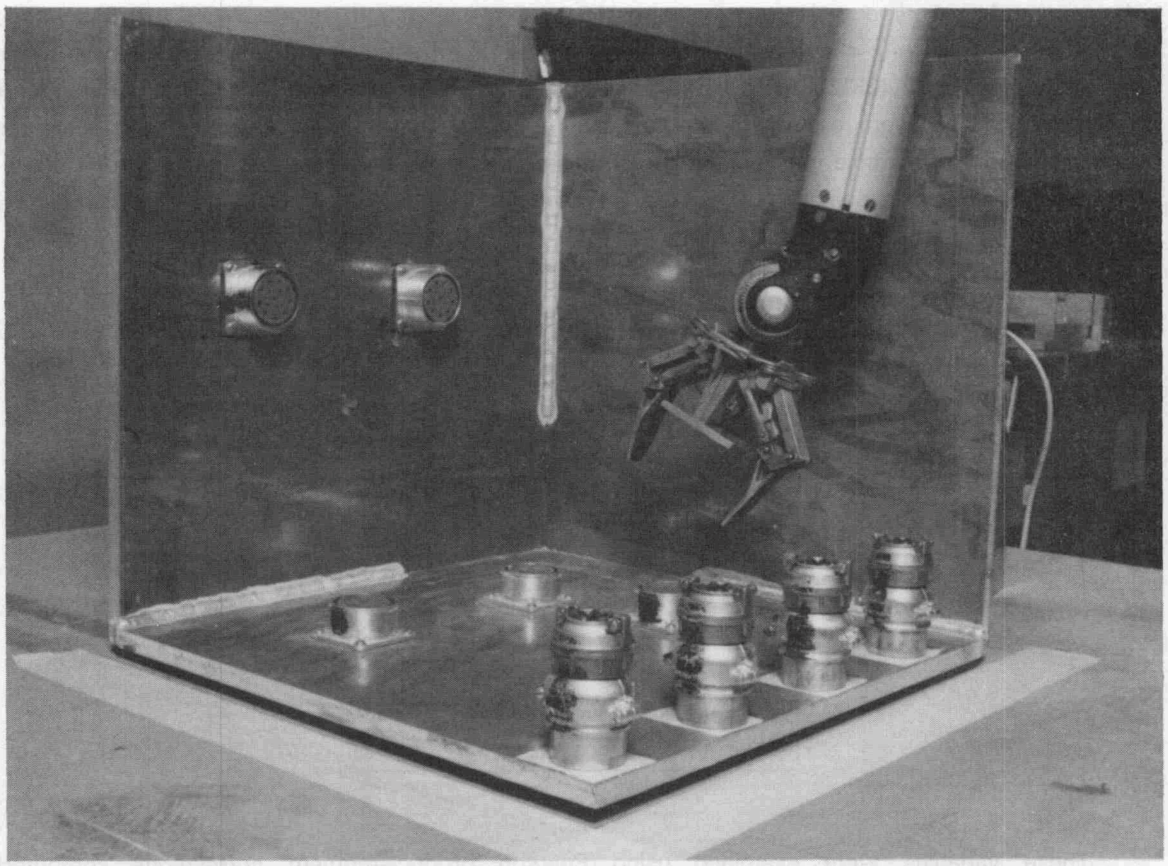

**Fig. 4. Electrical connector task.**

three times using both manipulators. In the last three repetitions (with camera in position 1), the operators were required to pass the stylus from the right manipulator to the left manipulator and insert the stylus into the station 3 target left-handed. After inserting the stylus into station 3, the operators withdrew the stylus and passed it back to the right-hand manipulator. They completed the circuit of the task board using the right-hand manipulator.

A trial consisted of three circuits of the task board. The time required to complete each trial was recorded.

No sooner than 1 d and no later than 5 d after completing the MOST, the subjects were called back to the testing area to complete the criterion task. Each operator completed this task three times with the television camera in position 1 and three times with the camera in position 2. The time required to complete each trial was recorded.

## 3.2 RESULTS

### 3.2.1 Dependent Variables

Dependent variables used in the analysis of data included (1) the average time required to complete the MOST task with the camera in position 1 (abbreviated MOS1), (2) average MOST time with camera in position 2 (MOS2), (3) average MOST time with camera in position 3 (MOS3), (4) average MOST time with camera in position 1 and using both hands (MOS2H), (5) average criterion task time with the camera in position 1 (CRI1), (6) average criterion task time with the camera in position 2 (CRI2), and (7) the overall average (both camera positions) of criterion task time (CRIALL). The averages were computed within operators so that, for example, there were ten scores on the first variable (one per operator), each an average of ten scores made by one operator with the camera in position 1. Table 2 lists overall averages and standard deviations observed for each of the dependent variables.

**Table 2. Averages and standard deviations**

| Variable | No. of cases | Average | Standard deviation |
|---|---|---|---|
| MOS1 | 10 | 57.25 | 24.92 |
| MOS2 | 10 | 88.60 | 54.81 |
| MOS3 | 10 | 111.00 | 49.66 |
| MOS2H | 9 | 149.04 | 84.17 |
| CRI1 | 10 | 262.27 | 161.00 |
| CRI2 | 9 | 232.89 | 104.18 |
| CRIALL | 10 | 264.37 | 149.47 |

These variables were examined using Pearson product-moment correlations computed between pairs of variables by the Statistical Analysis System's (SAS) PROC CORR.[3] Correlations express the degree and direction of a relationship between two variables. Correlations range between +1 and −1. High positive correlations indicate a strong relationship between variables, with values on one tending to be high when values on the other are high, and low when values are low on the other. Negative correlations indicate that high values on one variable are accompanied by low values on the other, and low values on the first are accompanied by high values on the other.

Table 3 lists the correlation coefficients. Performance of the MOST task with the camera in position 1 is correlated with performance of the criterion task with the camera in the same position. MOST performance is not significantly correlated with performance of the criterion task with the camera in position 2; however, performance of the MOST with the same camera position exhibited a correlation with CRI2 just short of significance. Overall, the correlations indicate that there is some relationship between MOST performance and criterion task performance, and further analysis to determine a predictive equation is justified.

**Table 3. Pearson product-moment correlations**

| | MOS2 | MOS3 | MOS2H | CRI1 | CRI2 | CRIALL |
|---|---|---|---|---|---|---|
| MOS1 | 0.52 | 0.36 | 0.68[a] | 0.80[b] | 0.58 | 0.82[b] |
| MOS2 | | 0.75[b] | 0.42 | 0.06 | 0.19 | 0.12 |
| MOS3 | | | 0.46 | 0.18 | 0.62 | 0.31 |
| MOS2H | | | | 0.35 | 0.59 | 0.47 |
| CRI1 | | | | | 0.84[b] | 0.98[b] |
| CRI2 | | | | | | 0.95[b] |

[a]Significant at alpha < 0.05 (alpha is the probability that a correlation in a sample of this size could be as observed if the correlation in the population is actually Ø).

[b]Significant at alpha < 0.01.

Next, selected variables were included in a multiple linear regression equation to ascertain the predictive ability of the skill test as a whole. The general form of the equation was:

$$\text{CRIALL} = f(\text{MOS1, MOS2, MOS3, MOS2H}).$$

CRIALL was selected as the criterion score in this phase of the analysis because of the high correlation between scores on the electrical connector task performed in position 1 and in position 2 ($r$ = 0.84; alpha ≤0.01). Alpha is the probability that a correlation this high could be observed in a sample from a population where the true correlation is zero. Including both scores as separate variables was not deemed necessary.

The regression was conducted using SAS PROC GLM.[3] Table 4 lists statistics calculated by an analysis of variance procedure[4] conducted to test each independent variable's predictive power, and Table 5 lists the regression coefficients for the model. The analysis indicates that MOST times are good predictors of criterion task times. The multiple correlation (multiple correlation is a correlation coefficient that expresses the relationship between a set of more than one predictor variable

**Table 4. ANOVA results (regression model, including MOS2H)**

| Source | DF | Sum of Squares | Mean Square | $F^a$ | Alpha[b] | $R^{2\,c}$ |
|---|---|---|---|---|---|---|
| Model | 4 | 91,578.41 | 22,894.60 | 13.84 | 0.0130 | 0.93 |
| MOS1 | 1 | 37,720.52 | 37,720.52 | 22.80 | 0.0088 | |
| MOS2 | 1 | 23,403.64 | 23,403.64 | 14.15 | 0.0197 | |
| MOS3 | 1 | 27,980.97 | 27,980.97 | 16.92 | 0.0147 | |
| MOS2H | 1 | 2,473.28 | 2,473.28 | 1.50 | 0.2885 | |
| Error | 4 | 6,616.32 | 1,654.08 | | | |
| Total | 4 | 98,194.72 | | | | |

[a]*F* is a statistic calculated to determine the strength of the contribution of each variable to the predictive power of the equation. If the contribution is negligible, *F* will be near 1.

[b]Alpha is the probability that an associated *F* statistic would be as high as observed in the experimental sample if the contribution of the predictor variable is negligible in the entire population.

[c]$R^2$ is a measure of the predictive power of the complete regression equation. It ranges from 0 to 1.0, with high values indicating good predictive power.

**Table 5. Regression equation coefficients (model including MOS2H)**

| Source | Coefficient |
|---|---|
| INTERCEPT | −119.5608 |
| MOS1 | 8.1454 |
| MOS2 | −2.6415 |
| MOS3 | 1.8719 |
| MOS2H | −0.3025 |

and one criterion variable) between combined MOST scores and performance of the electrical connector was quite high ($R = 0.97$). Three of the predictors (MOS1, MOS2, and MOS3) were found to be statistically significant (that is, alpha $\leq 0.05$) contributors to the regression; one (MOS2H) was not related to electrical connector task performance in a statistically significant way. A plot of predicted scores versus observed connector task times indicated that the linear model is appropriate (Fig. 5 is the plot) for these data.

Further regression analyses were performed to identify the best predictive model. Subsets of the predictor variables (MOS1, MOS2, MOS3, and MOS2H) were included in separate regressions to determine which combination produced the highest $R^2$. ($R^2$ is the square of the multiple correlation coefficient; it is an index of the predictive power of the regression equation.) Table 6 lists statistics calculated by the analysis of variance procedure, and Table 7 lists the regression coefficients for the best model found. This model excludes the variable MOS2H from the equation. The

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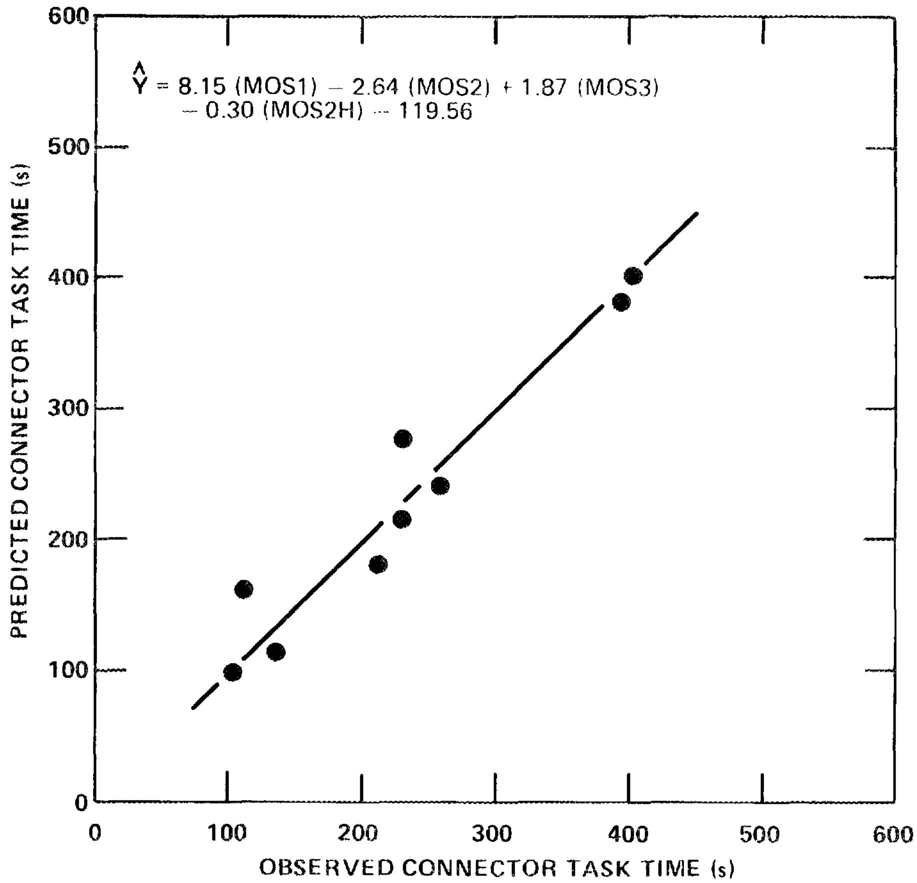


Fig. 5. Observed and predicted connector task times.

**Table 6. ANOVA results (best regression model, excluding MOS2H)**

| Source | DF | Sum of squares | Mean square | $F$ | Alpha | $R^2$ |
|---|---|---|---|---|---|---|
| Model | 3 | 191,450.15 | 191,450.15 | 39.75 | 0.0002 | 0.95 |
| MOS1 | 1 | 136,650.68 | 136,650.68 | 85.12 | 0.0001 | |
| MOS2 | 1 | 26,238.60 | 26,238.60 | 16.35 | 0.0068 | |
| MOS3 | 1 | 28,560.87 | 28,560.87 | 17.79 | 0.0056 | |
| Error | 6 | 9,631.78 | 1,605.30 | | | |
| Total | 9 | 201,081.93 | | | | |

**Table 7. Regression equation coefficients (model excluding MOS2H)**

| Source | Coefficient |
|---|---|
| INTERCEPT | −86.0620 |
| MOS1 | 6.4492 |
| MOS2 | −2.3748 |
| MOS3 | 1.7262 |

analysis indicated that the linear equation combining performance of the MOST task in the different camera positions was a very accurate predictor of criterion task performance ($R = 0.98$), and plotting the predicted vs actual connector task times indicated that the linear model is appropriate (Fig. 6 is the plot). All three independent variables included in the equation were statistically significant predictors of electrical connector task performance.

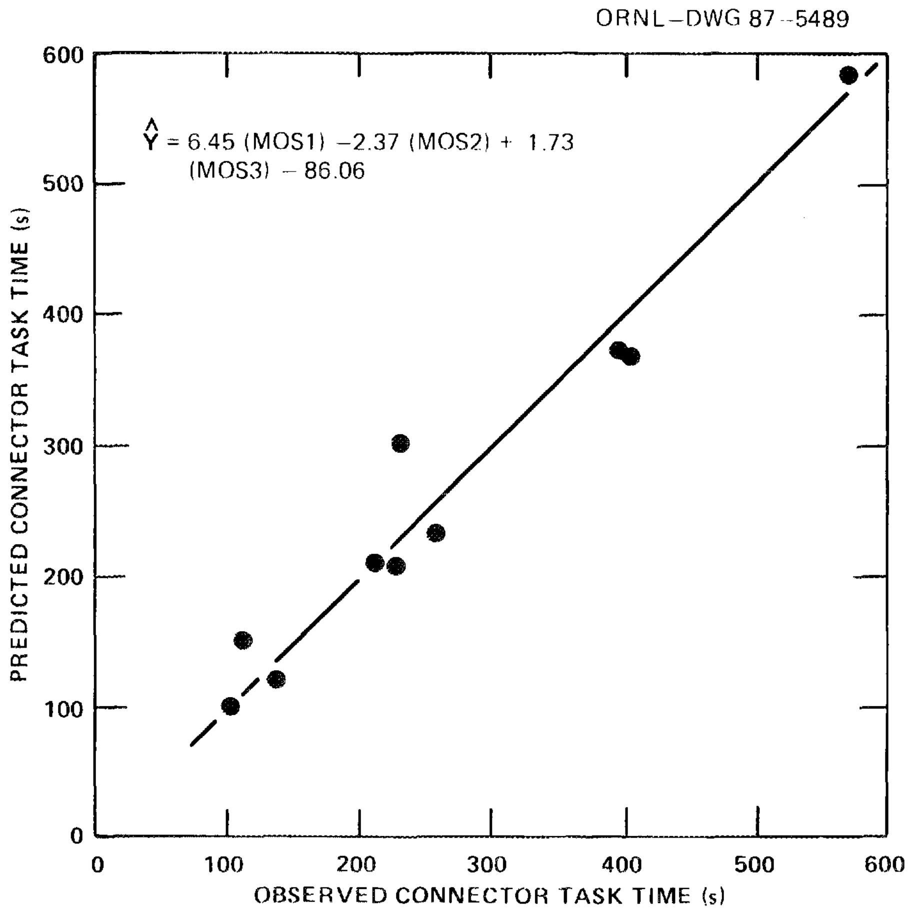


Fig. 6. Observed and predicted connector task times, model excluding MOS2H.

## 4. DISCUSSION

The high level of predictive power exhibited by the MOST for the electrical connector task is evidence that it validly measures manipulator operator skills. However, the power of prediction observed in these data is probably higher than can be expected for other tasks. The electrical connector task matches the MOST very closely in terms of the subtasks comprising it. Other tasks will not be predicted with the same high power if they include different subtasks. For the majority of test-stand tasks, the MOST should exhibit high predictive power, but for tasks involving other subtasks, its power will not be as good.

Although the best model found for predicting time to complete the electrical connector task excluded the time required to complete the skill task in its two-handed version, it is not appropriate to exclude that version of the task from future skill testing. While the electrical connector task did not require two-handed operation, some of the tasks on the test-stand will involve two-handed manipulation. These tasks may be predicted better by a version of the MOST which includes two-handed completion of the skill test task.

It is interesting to note that while novices were easily distinguishable from the other operators, there were no obvious differences between experienced operators and the subjects who had limited operational experience but who had observed remote handling in the past. This implies that observation of remote manipulation serves as practice. Persons who observe remote manipulation become skilled at it. This may be evidence that the perceptual skills required for remote handling, primarily the ability to extract useful information from televised views of the remote area, have as great an impact on task performance as do motor skills. Observers may learn to make accurate perceptions of remote scenes. This may help them perform well with manipulators. Remote-handling strategies may also be learned through observation. Observers exposed to the methods of good and poor operators come to learn which strategies are effective and which are ineffective. Observers are then able to apply their experience during later performance of remote handling tasks.

A valid test of manipulator operator skill has several potential uses. It may aid in performance testing by allowing precise matching of between-group skill levels. It may be used to access the impact of training programs or to identify candidate operators. It may also be used as a criterion task for even more simple measures (perhaps even pencil and paper tests) of operator skill.

Future testing at ORNL will be aimed at reducing the number of task repetitions necessary for accurate skill measurement and at using the skill test to assess the effectiveness of training programs.

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