SRI Project 7696
JPL Contract 95-5170

STUDY OF MODELING AND EVALUATION OF REMOTE MANIPULATION TASKS WITH FORCE FEEDBACK

Final Report

(NASA-CR-158721) STUDY OF MODELING AND EVALUATION OF REMOTE MANIPULATION TASKS WITH FORCE FEEDBACK Final Report (SRI International Corp., Menlo Park, Calif.) 40 p HC A03/MF A01 CSCL 05E G3/54

N79-26785

Unclas 27829

By: John W. Hill, Senior Research Engineer
Artificial Intelligence Center
Computer Science and Technology Division

Prepared for:

Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91103

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

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SRI International
333 Ravenswood Avenue
Menlo Park, California 94025
(415) 326-6200
Cable: SRI INTL MNP
TWX: 910-373-1246

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Approved:

Peter E. Hart, Director
Artificial Intelligence Center

David H. Brandin, Executive Director
Computer Science and Technology Division

ABSTRACT

This report describes the use of time and motion study methods to evaluate force feedback in remote manipulation tasks. Several systems of time measurement derived for industrial workers were studied and adapted for manipulator use. Next a task board incorporating a set of basic motions was designed and built. The task board was equipped with switches to sense the beginning and end of each motion and was connected to a digital data recorder that automatically timed each move. Results obtained from two subjects in three manipulation situations for each are reported: a force-reflective manipulator, a unilateral manipulator, and the unaided human hand. The results indicate that (1) a time-and-motion study techniques are applicable to manipulation, and that (2) force feedback facilitates some motions (notably fitting), but not others (such as positioning). It is pointed out that this approach can be used to compare and optimize different methods for performing remote-manipulation tasks and that it appears to have the same wide applicability to remote handling and assembly as it has had to industrial manual tasks.

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This work was sponsored by the Jet Propulsion Laboratory, Advanced Teleoperator Technology Development project, supported by the NASA Life Sciences Office. The work was monitored by A. K. Bejczy of JPL. John W. Hill was the SRI project leader.

The author would like to express his thanks to Peter Bringham and E. Calhoun at Lawrence Berkeley Laboratories, Berkeley, California, for the use of their manipulation facility with the Model H manipulator. Mr. Calhoun served as a subject in the experiment.

The author would also like to thank John Simon of Fermi National Laboratories, Batavia, Illinois, for donating his time and laboratory, including the use of an E-4 servo-controlled, force reflecting manipulator. Unfortunately a power failure occurred midway through our scheduled experiment in Batavia. Because blizzard conditions made it impossible to repair the situation in time, the data for that experiment are not available in this report.

I INTRODUCTION

The main objectives of this project are to:

- Consider the types of tasks that will be performed by space manipulators, choose a complex task, and resolve it into elemental subtasks.
- Conduct an experimental study with force-and non-force-reflecting manipulators, and determine how the performance on the complex assembly task can be predicted from performance on the elemental tasks for the various experiments.
- Outline a mathematical basis for predicting performance of a complex task from elemental task performance.

To determine the type of tasks that will be performed by space manipulators, NASA's plans in this area were studied. In particular the proceedings of applicable workshops [1,2] of the "NASA Study Group on Machine Intelligence and Robotics," of which the author is a member, were surveyed. Space manipulation requirements emerge in the following typical projects:

- Arm for geological experiments on the Mars rover
- Arm for construction by the space shuttle
- Remote systems for assembling solar-power collectors
- Free-flying teleoperator for service and repair.

A survey of the basic motions involved (material handling, object acquisition, assembly, repair, etc.) reveals that the types of tasks that will be performed using space manipulators are basically the same ones that have been performed using remote manipulators on earth. This is further substantiated by space application experiments at Argonne National Laboratory [3], where the disassembly of a propellant utilization valve from a J-2 engine was evaluated as carried out by a hot-cell manipulator.

Our approach to this project is based on the application of time and motion systems developed by industrial engineers to remote manipulators. These systems were originally developed to establish data for the scientific measurement of human effort. They have enabled those interested in the industrial engineering field to develop answers to handling and assembly problems quickly, consistently, and with greater understanding of the underlying causes surrounding them.

The remote-manipulation situation is far more diverse than direct handling by human workers because of the variety of manipulators (different rates of movement, servo lags, and degrees of force reflection). Application of time studies to manipulators may quantify the way different manipulator characteristics affect performance. As in industrial engineering, the ways in which these measurement techniques can be applied to remote manipulation are summarized in the following categories:

- Development of effective methods and plans prior to system operation.
- Improvement of existing methods.
- Development of standard time formulas (models).
- Cost estimations.
- Designing of equipment to be handled.
- Selection of effective equipment and tools for remote handling.
- Operator training.

II ADAPTION OF TIME AND MOTION STUDIES TO MANIPULATORS

There is much historical precedent for classification at the unit level of task complexity. The prototype system was developed by Taylor in the 1880's (reprinted in Taylor [4]), and refined by Gilbreth [5] in a continuing effort to establish standard times for industrial operations. The current proliferation of predetermined time systems (Methods-Time Measurement, Work-Factor, Motion-Time Analysis, and Basic Motion Time Study, to name some of the major systems) indicates the high level of continuing interest. (A concise description of the above-mentioned systems can be found in the Industrial Engineering Handbook [6]).

The utility of such systems lies in their ability to synthesize almost any industrial operation by the proper combination of units. For instance, Table 1 lists the classifications used in the Methods-Time Measurement system. Each of the listed classifications is further divided so that any operation can be described. For use in predicting task completion times, the time required for every unit would be found by reference to the appropriate entry in the classification list and the unit times would be totaled.

Table 1

METHODS TIME MEASUREMENT UNIT TASK DESCRIPTIONS

Operation	Description
REACH	basic hand or finger motion employed to move the hand or fingers to a destination
MOVE	basic hand or finger motion employed to transport an object to a destination
TURN	basic motion employed to rotate the hand about the long axis of the forearm
APPLY PRESSURE	application of muscular force to overcome object resistance, accomplished by little or no motion
GRASP	basic finger or hand element employed to secure control of an object
RELEASE	basic finger or hand motion employed to relinquish control of an object
POSITION	basic finger or hand element employed to align, orient, and engage one object with another to attain a specific relationship
DISENGAGE	basic hand or finger element employed to separate one object from another object where there is a sudden ending of resistance
CRANK	basic motion employed when the hand follows a circular path to rotate an object, with the forearm pivoting at the elbow and the upper arm essentially fixed.

Blackmer [7] and Black [8] used a similar unit classification for analysis of manipulator system results. In their work, a partial goal was to isolate those portions of an element-level task that were most sensitive to the design variable being studied (time delay).

McGovern [9] and Hill [10, 11] showed how subtasks carried out with manipulators can be completely broken down into unit motions and that the resulting constituent tasks are compatible with Fitt's Law [12], a widely accepted and proven formula for both hand and manipulator performance.

This approach may be applied to manipulators with the following modifications:

(1) REACH is not appropriate for manipulators, since there is always an object (the master or control brace) in the operator's hand. MOVE is always used for motions.

(2) GRASP is simplified, since there are no dexterous fingers on manipulators. Instead of simply moving the human hand to within 60 mm of the object and closing it, we must move the manipulator, position the grip, and then close the grip. There is only one grasp parameter: time to close the grip.

(3) POSITION is broken down into two units; PRE-POSITION and INSERT, based on Hill's results [11] with three manipulators.

(4) DISENGAGE is the time required to separate objects along a constrained trajectory.

Table 2

UNIT TASK DESCRIPTIONS FOR MANIPULATORS

Operation	Description
MOVE (d)	basic motion employed to transport end-effector a distance d (measured in millimeters)
TURN (a)	basic motion employed to rotate the end-effector about the long axis of the forearm an angle a (measured in degrees)
APPLY PRESSURE	application of force to overcome object resistance -- accomplished by little or no motion.
GRASP	basic motion to close end-effector and secure control of an object.
RELEASE	basic motion to open end-effector and relinquish control of an object.
PRE-POSITION (t)	basic hand element to align and orient one object with another within a tolerance t, measured in millimeters.
INSERT (t)	basic hand motion employed to engage objects along a trajectory with a tolerance t, measured in millimeters.
DISENGAGE (t)	like INSERT, but employed to separate objects.
CRANK	basic motion employed when the hand follows a constrained circular path to rotate an object, with the forearm pivoting at the elbow and the upper arm essentially fixed.
CONTACT	processing time for holding down a lift-off switch.

III DESIGN OF MANIPULATION EXPERIMENT

An experimental task board was designed to permit measurements of all the motion elements enumerated in Table 2. It included several complete tasks, any of which could be used for verifying the basic concept (model) of adding up individual unit times to obtain the total task time. The task board was instrumented with switches to enable automatic recordings of the unit task elements. Similar but simpler task boards for evaluating human motion times were used by Annett, Golby, & Kay [13] (using electrical contact between metallic peg and metallic receptacle) and by Buffa [14] (using push-button switches and electronic counters to measure five basic motions).

A. Task Board

The task board, shown in Figure 1, is instrumented for seven different tasks, some with a variety of tolerance tools and movement distances. Each contact point is equipped with microswitches to detect the raising of a tool or the touching of a contact point. The receptacle has a light spring-loaded plunger that follows the tool as it descends. The task board sensing switches are described individually in Table 3.

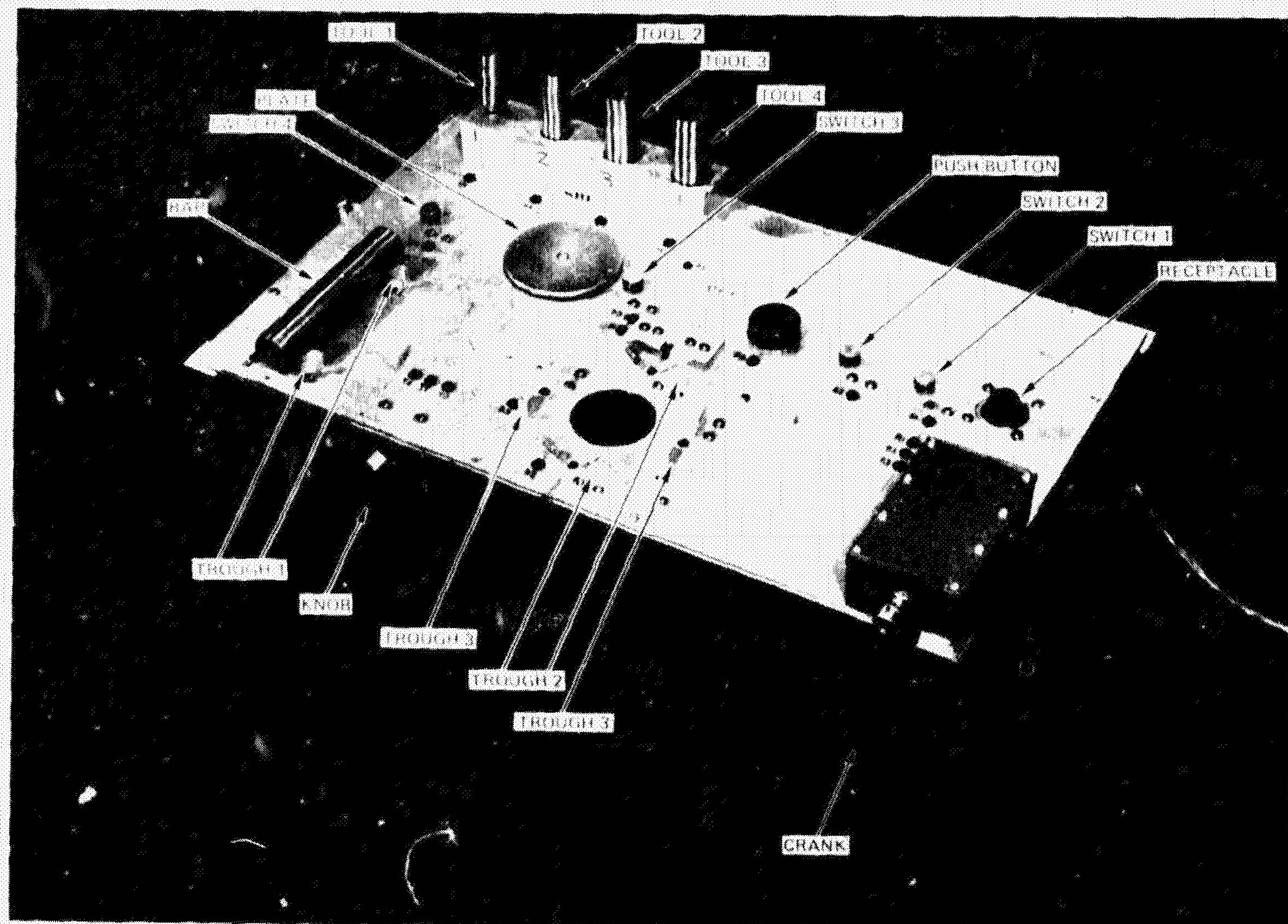

FIGURE 1 TASK BOARD WITH FARTS IDENTIFIED

Table 3

DESCRIPTION OF TASK BOARD SENSING SWITCHES

Switch	Description
Tool 1	25.4-mm-diameter bar reduced to 6.4 mm diameter at end
Tool 2	round bar 19.1 mm in diameter
Tool 3	round bar 23.8 mm in diameter
Tool 4	round bar 25.0 in diameter
Receptacle	25.4-mm-diameter hole, 25.4 mm deep. Central plunger activates switch R1 when tool is 12 mm above the opening, switch R2 when tool tip enters 3 mm into opening, and switch R3 when tool tip is seated 3 mm from the bottom of hole.
Switch 1	12.7-mm-diameter button located 50 mm from receptacle. Switch closes when button is depressed.
Switch 2	like Switch 1, located 100 mm from receptacle
Switch 3	like Switch 1, located 250 mm from receptacle
Switch 4	like Switch 1, located 400 mm from receptacle
Push Button	button located inside a 25.4 mm-ID tube. Requires 4 Nt force to close; located 150 mm from receptacle.
Plate	76.2-mm-diameter disk. Switch closes when disk is depressed; located 200 mm from receptacle.
Crank	76.2-mm-long handle. Rotary switch senses start position (handle down) and half-turn position (handle up), located 400 mm from plate.
Knob	12.7 X 38-mm knob. Rotary switch senses left and right half turns (+90 degrees), located 250 mm from plate.

Bar	25.4-mm-diameter X 12.7-mm-long rod.
Trough 1	two V-notch supports located 101.6 mm apart. Switches at the base of each close when bar is present, center located 150 mm from plate.
Trough 2	like Trough 1, center located 200 mm from Trough 1, 150 mm from plate.
Trough 3	like Trough 2, but horizontal.

B. Task Descriptions

Seven tasks with different basic strategies were devised to enable all the basic motion elements described in Table 2 to be measured. Descriptions of these tasks, broken down into unit elements, are presented here.

1. Peg-in-Hole Task

In this task the subject first grasps one of the four tools from the tool holder. He then contacts one of the switches with the tool tip, moves it to the receptacle -- inserting it all the way -- and returns the tool tip to the switch. This process is performed six times before changing to a new tool or switch

The element breakdown for Tool 3 (diameter 23.8 mm) and Switch 1 (diameter 12.7 mm; distance 50 mm) is as follows:

MicroSwitch	Motion Element
Lift-off Switch 1 off	contact (switch)
Receptacle 1 on	move (50) + pre-position (12.7 + 23.8)
Receptacle 2 on	position (25.4 - 23.8)
Receptacle 3 on	insert (25.4 - 23.8)
Receptacle 3 off	contact (bottom of receptacle)
Receptacle 2 off	disengage (25.4 - 23.8)
Lift-off Switch 1 on	move (50) + pre-position (12.7 + 23.8)

This task is repeated with all four switches to obtain moves of 50, 100, 250, and 400 mm, and with all four tools to obtain positionings, insertions, and disengagements of 19, 6.4, 1.6, and 0.4 mm.

2. Push-Button Task

To begin this task the subject grasps Tool 1 and alternately contacts the switch and then the pushbutton six times. The element breakdown for Switch 2 (distance 50 mm) is as follows:

Microswitch	Motion Elements(s)
Lift-off Switch 1 off	contact
Pushbutton on	move (50) + pre-position (19.0) + apply force
Pushbutton off	contact
Lift-off Switch 1 on	move (50) + pre-position (19.0)

This task is repeated with Switch 2, Switch 1, and Switch 4 to obtain moves of 50, 100, and 250 mm. Subtracting the two movement times yields the time required to apply force.

3. Plate-Touch Task

To begin this task the subject grasps Tool 1 or Tool 4 and alternately makes contact six times between one of the switches and the plate. The element breakdown for Switch 3 and Tool 4 is as follows:

Micro-Switch	Motion Elements
Switch 3 off	contact
Plate on	move (50) + pre-position (101.6)
Plate off	contact
Switch 3 on	move (50) + pre-position (38.1).

This task is repeated with Switch 3, Switch 4, and Switch 1 to obtain moves of 50, 100, and 250 mm. This task was included to obtain positioning times for large tolerances (100 mm) corresponding to the basic motion element "move to approximate or indefinite location" in the MTM system.

4. Knob-Turn Task

To begin this task the subject touches the plate, then grasps the vertical handle of the rotary switch, turns it 90 degrees clockwise, 180 degrees counterclockwise, and 90 degrees clockwise (to its original vertical position); he then releases the knob and touches the plate once more. The element breakdown for this task is as follows:

Microswitch	Motion Elements
Plate off	contact
T1 on	move (250) + grasp knob
T2 on	turn (+90 degrees)
T2 off	dwell time
T3 on	turn (-180 degrees)
T3 off	dwell time
T1 off	turn (+90 degrees)
Plate on	release + move (250) + pre-position (76.2)

Switch T1 is off when the knob is vertical; Switches T2 and T3 are on when the knob is turned 90 degrees clockwise or counterclockwise.

5. Crank-Turn Task

In this task the subject touches the plate (with hand empty), then grasps the handle of the crank, turning it three times clockwise, releases the handle, and returns to the plate. The task consists of repeating this procedure six times. The element breakdown for this task is a follows:

Microswitch	Motion Elements
Plate off	contact
C1 on	move (400) + grasp crank
C2 off	crank (.5 turn)
C1 on	crank (.5 turn)
C2 off	crank (.5 turn)
C1 on	crank (.5 turn)
C2 off	crank (.5 turn)
C1 off	crank (.5 turn)
Plate on	release + move (400) + pre-position (76.2)

Switch C1 is off when the crank handle is straight down; C2 is on when the handle is straight up.

6. Pick-and-Place Task

In this task a round plastic bar 25.4 mm in diameter and 76 mm long is first stood on the plate. The subject then touches lift-off Switch 1, grasps the plastic bar, touches the same lift-off switch with the plastic bar, sets the bar on the plate, and returns to touch the lift-off switch. The element breakdown for this task is as follows:

Microswitch	Motion Element
Lift-off Switch off	contact
Plate off	move (250) + grasp bar
Lift-off Switch on	move (250) + pre-position (38.1)
Lift-off Switch off	contact
Plate on	move (250) + pre-position (50.8) + release bar
Lift-off Switch on	move (250) + pre-position (25.4)

This task was used primarily to obtain grasp and release times.

7. Bar-Transfer Task

The task consisted of touching the plate, picking up the bar from Trough 1, transferring it to Trough 2 (firmly seating the bar against a stop across the top of Trough 2), picking up the bar, rotating it 90 degrees, setting it down in Trough 3, touching the plate, picking up the bar in Trough 3, returning it to Trough 1, and finally returning to the plate. The element breakdown for this task is as follows:

Microswitch	Motion Element
Plate off	contact
Trough 1 off	move (150) + grasp bar
Trough 2 on	move (200) + pre-position (stop)
Trough 2/up on	reposition
Trough 2 off	contact
Trough 3 on	move (150) and turn (90) simultaneously + pre-position (stop)
Plate on	release + move (150) + pre-position (76.2)
Plate off	contact
Trough 3 off	move (150) + grasp bar
Trough 1 on	move (200) + pre-position (stop) + release
Plate on	move (150) + pre-position (76.2)

The trough switches each consist of two switches, one at the base of each of the two notches comprising the trough, wired in series. The trough switches close only when the bar is seated in both ends of the trough, 1.6 mm from the bottom. A separate Trough 2/up switch above Trough 2 indicates the bar is also pushed up against this stop.

C. Manipulators

Experiments were conducted with two different manipulators and the unaided human hand. One manipulator was the Model H located at Lawrence Berkeley Laboratory, shown in Figure 2. This is a cable-connected manipulator typical in performance to many used in hot cells. It provided a definite "feel" of the remote environment as objects were brought into contact. In the experiment the task board was placed inside the hot cell, while the operator, operating the master at shoulder level, stood viewing the task from a distance of about 2 meters.

The second manipulator was the Ames Arm at SRI International. The experimental setup is shown in Figure 3. Being unilateral, it provided no feel of the task; the subject, seated about 2 meters from the task board, relied on his sight only to accomplish the tasks.

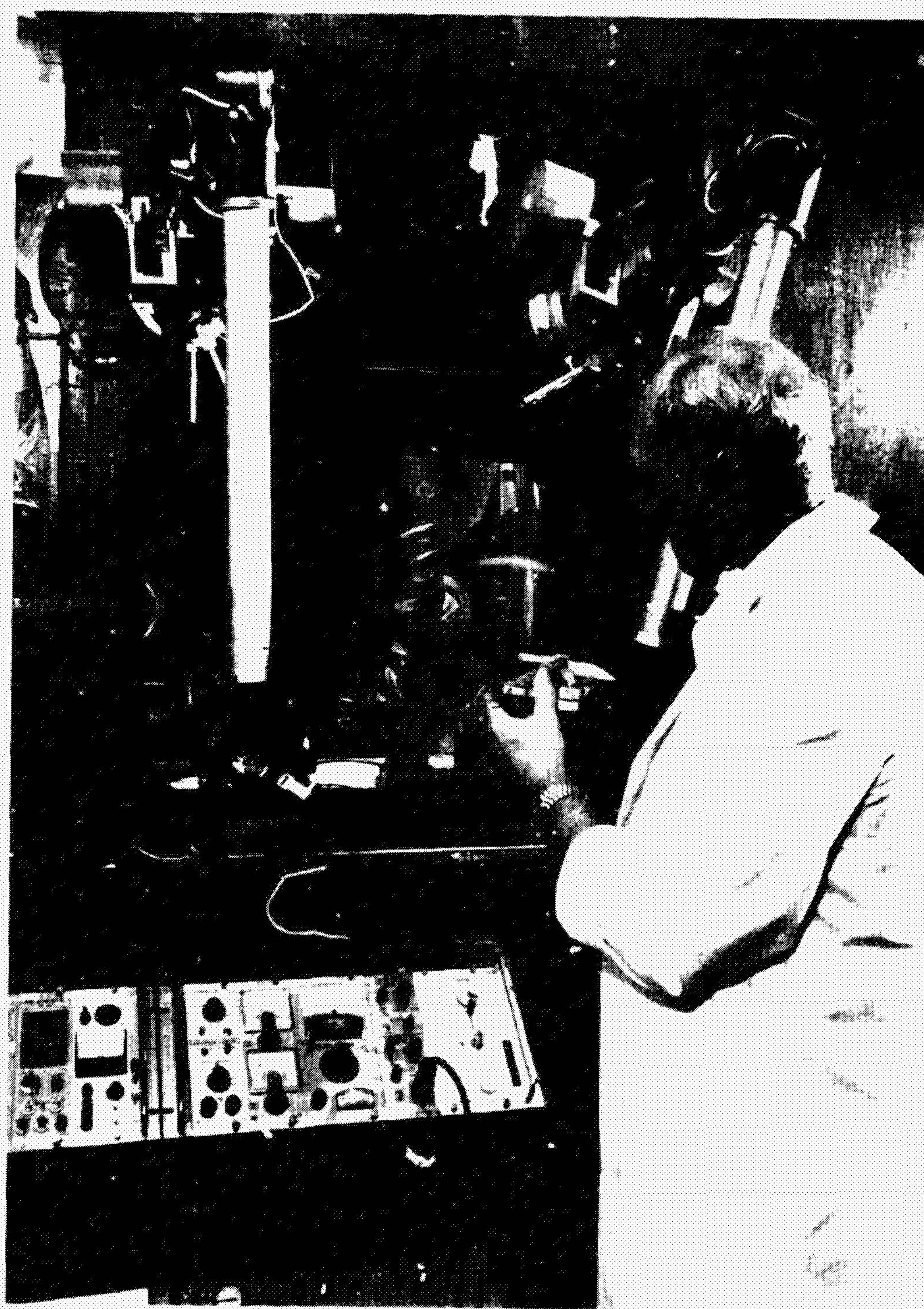

FIGURE 2 MODEL H MANIPULATOR AT LAWRENCE BERKELEY LABORATORY

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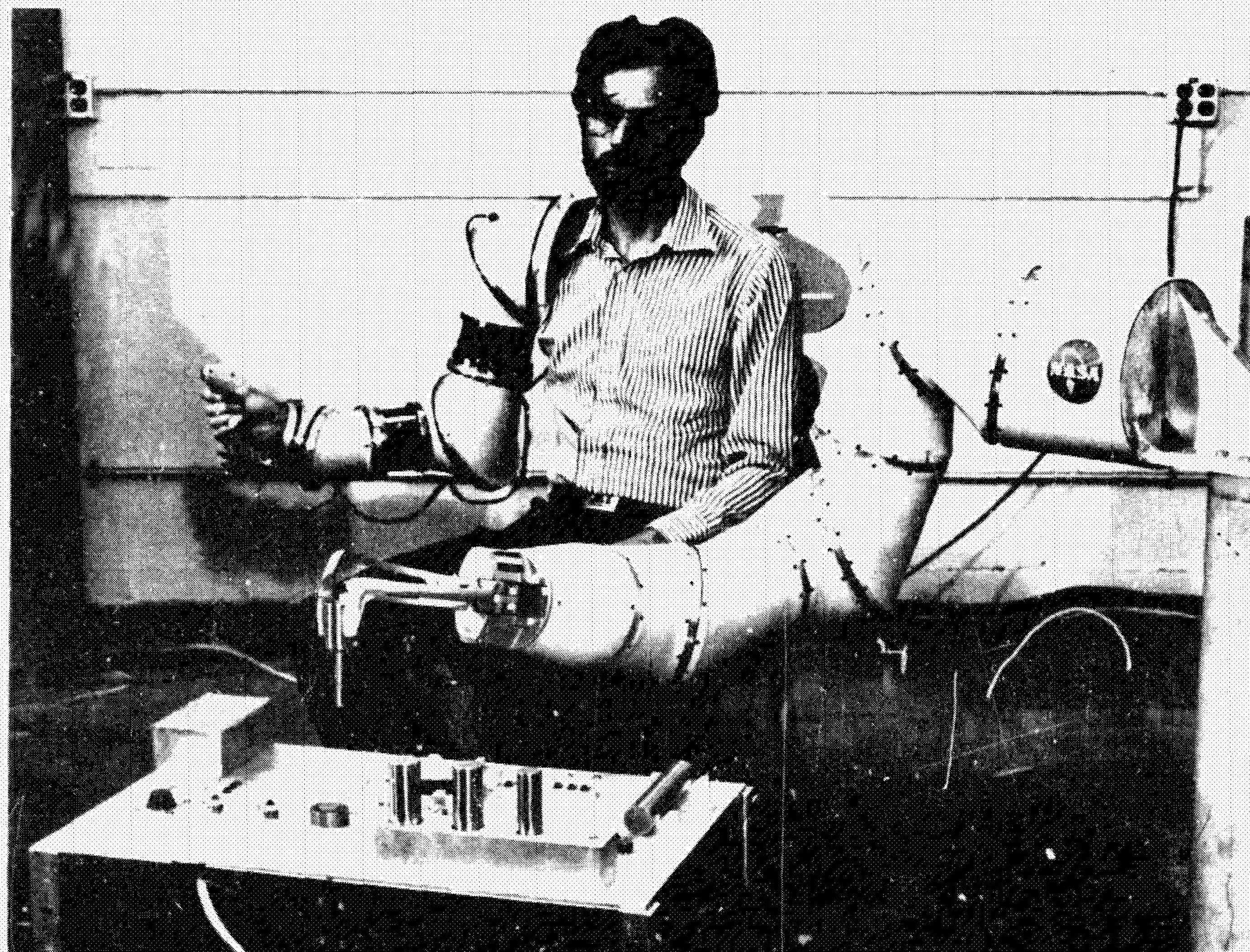


FIGURE 3 PERFORMING PEG-IN-HOLE TASK WITH AMES ARM

The third set of experiments was made using direct manipulation with the unaided human hand.

D. Subjects

For each manipulator the experimental series with six executions of each of seven tasks was run by two subjects. Prior to each task the subject performed several repetitions until it was clear that he had mastered the task.

E. Data Processing

Switch openings and closures were encoded into 8-bit words and punched on paper tape at the rate of 25 words per second. This rate was a little slow for some of the direct hand manipulations but was more than adequate for the remote manipulators. The paper tape was further processed by a digital computer to obtain times between switch closures, then processed manually to obtain average times for each of the individual motion elements.

IV EXPERIMENTAL RESULTS

All timings for the experiment obtained from computer printouts of switch timings were grouped manually into those for each basic motion element, for each subject, and for each manipulator. In this way, fitted to the data from 182 switch timings (6 measurements each) for one subject and one manipulator were only 31 basic motion elements (4 different inserts, 4 disengages, 7 pre-positions, 4 moves, 2 turns, 6 cranks, 1 contact, 1 grasp, 1 release, and apply force). This gave from 3 to 19 repeated timings for each basic motion element. The results for insert, disengage, turn, and crank which were obtained directly from the switch timings, are summarized in Figures 4, 5, 6, and 7.

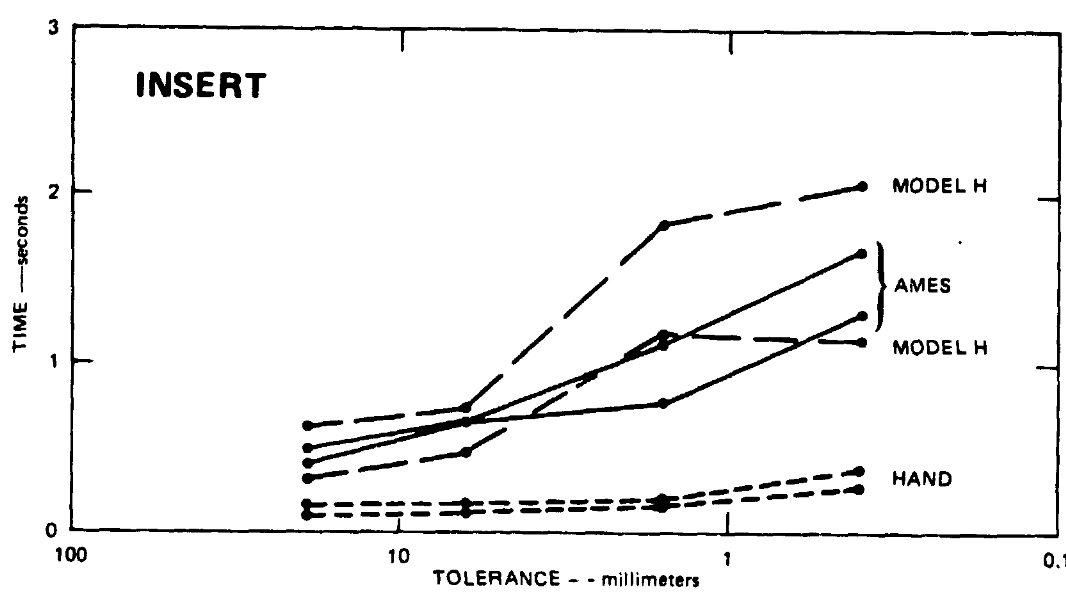


FIGURE 4 INSERT RESULTS

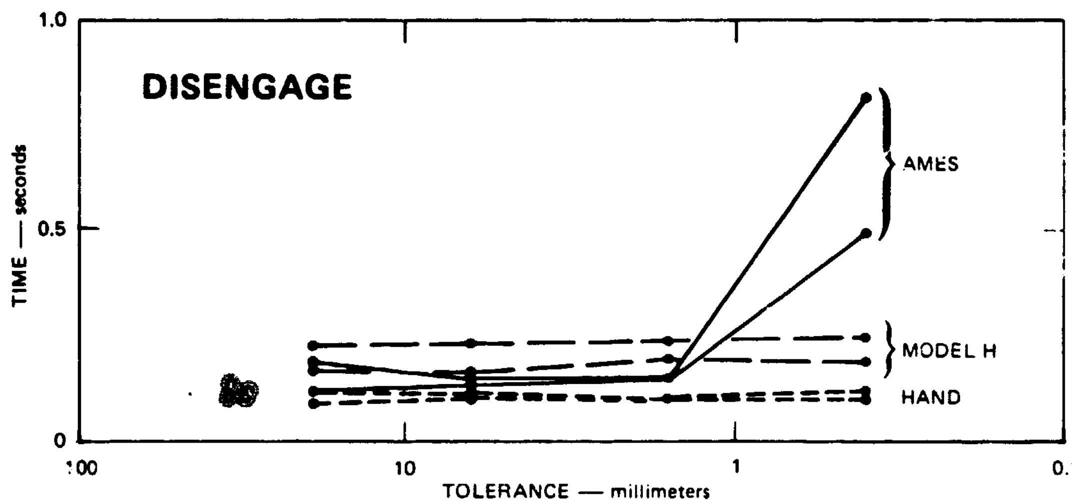


FIGURE 5 DISENGAGE RESULTS

The move and pre-position results, which always occur in combination, first had to be separated. This was accomplished using the timings of the protruding receptacle switch R1, which was included in the task board for this purpose. R1 enabled timing of pre-positioning from 19 mm (at first contact) down to 6.4, 1.6, and 0.4 mm (at contact of R2) to be obtained separately. Next these timings were subtracted from the movement times to give all moves a positioning tolerance of 19-mm each. Finally, the plate-touch results that gave pre-positioning times from 100 to 19 mm were used to find the 19 mm-positioning time (with 100-mm pre-positioning arbitrarily selected to take zero time). Separated and adjusted move and pre-position results are shown in Figures 8 and 9.

Grasp and release times given in Table 4 were obtained by subtracting move times from the corresponding move + grasp times available. Contact times were obtained directly from the lift-off switch, receptacle bottom switch (R3), push-button switch, and plate

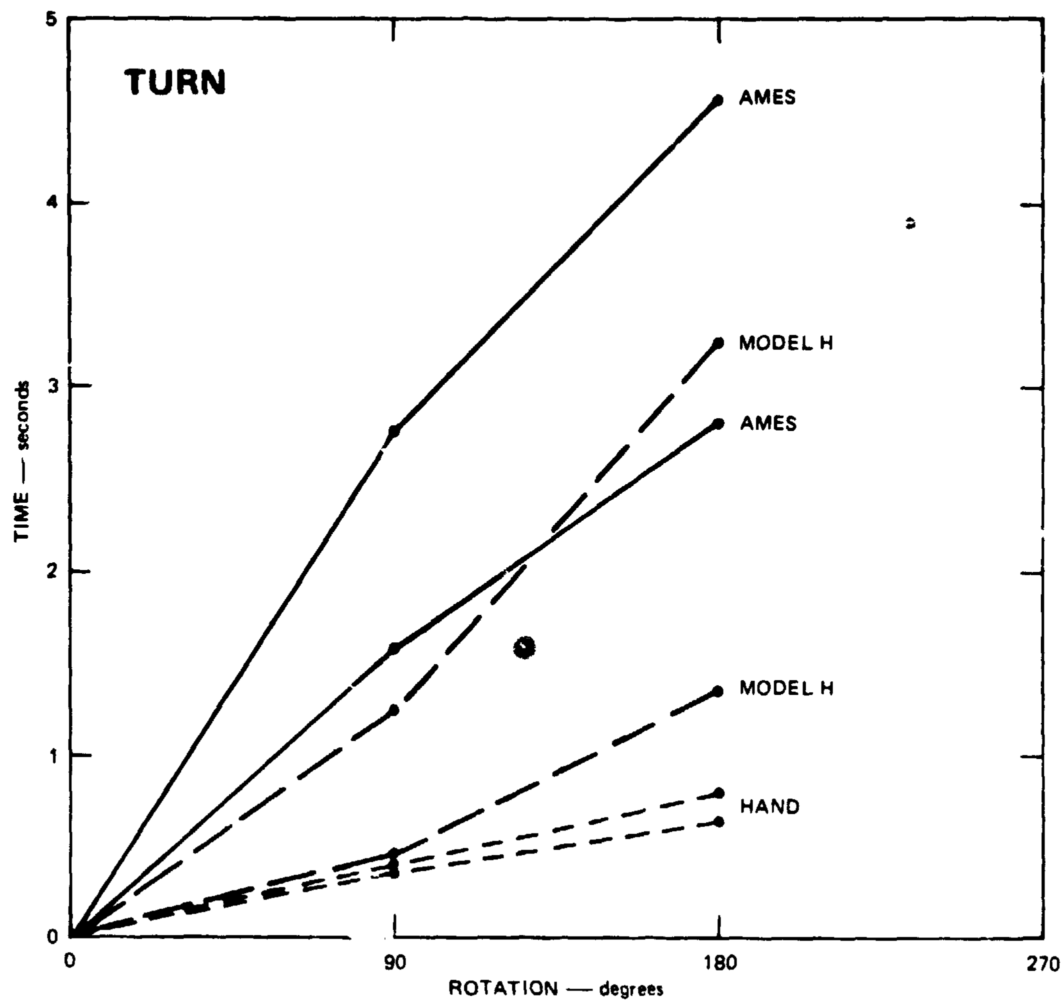


FIGURE 6 TURN RESULTS

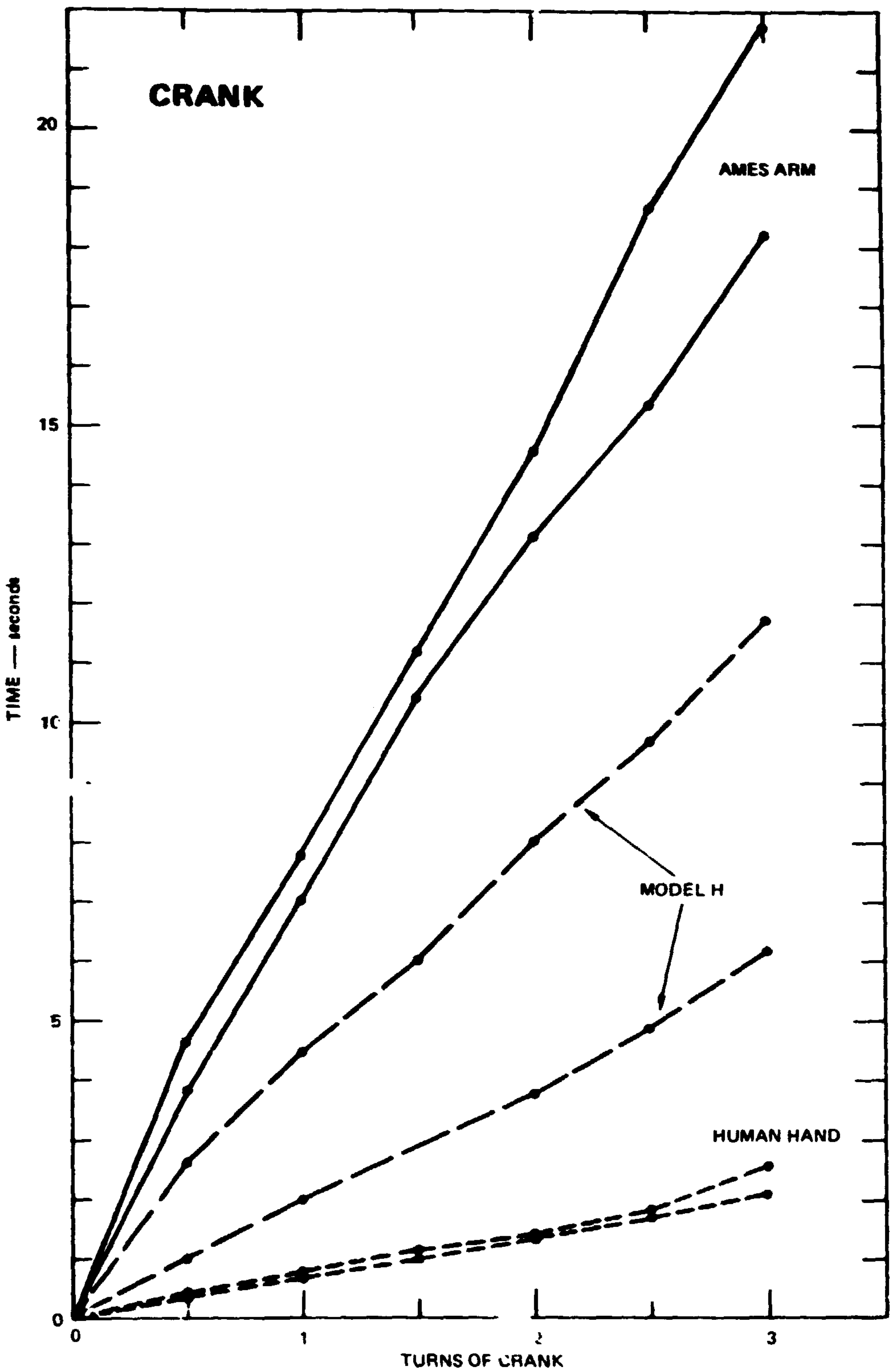


FIGURE 7 CRANK RESULTS

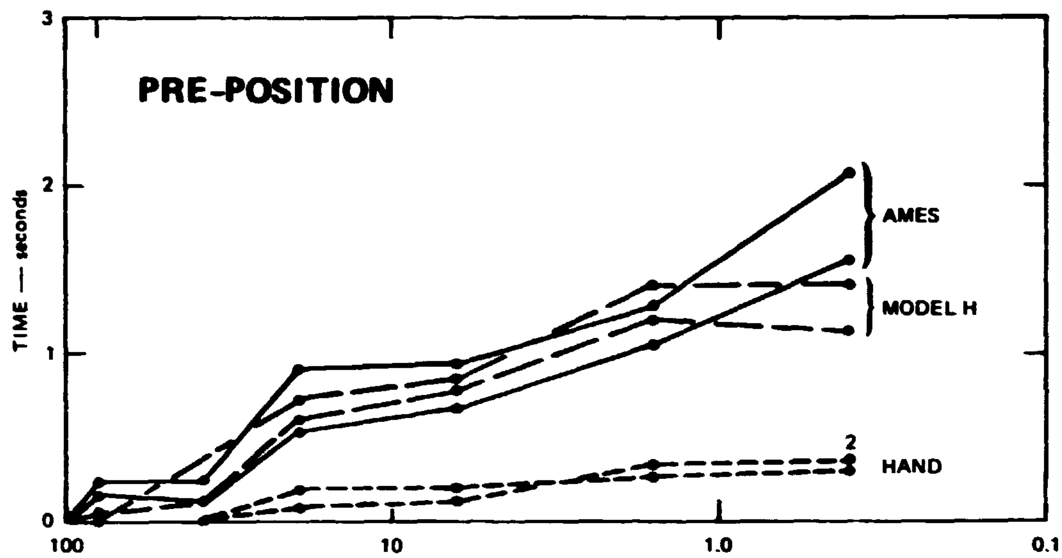


FIGURE 8 PRE-POSITION RESULTS

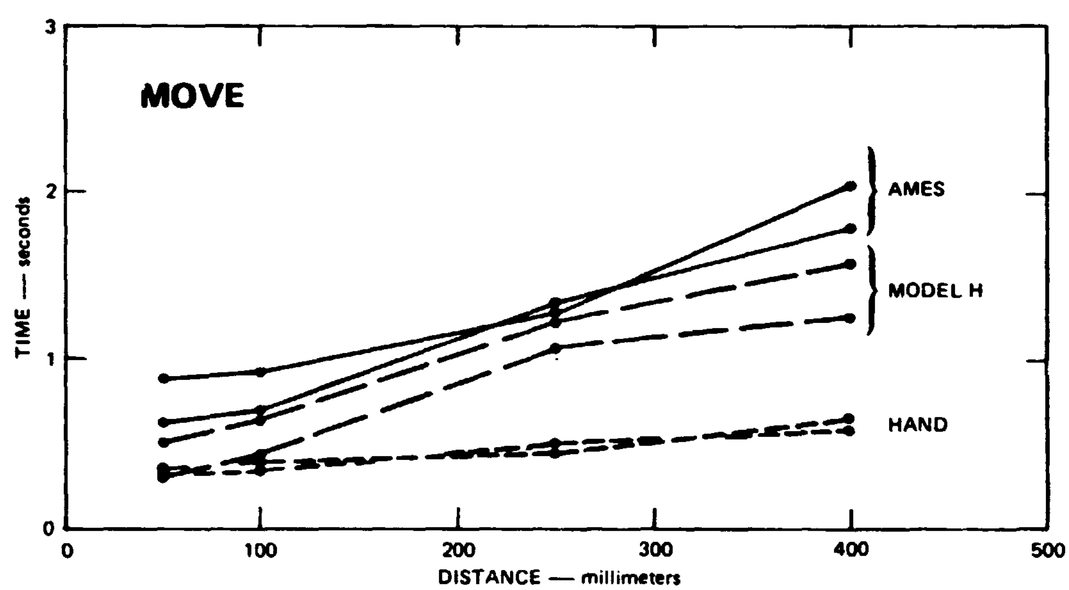


FIGURE 9 MOVE RESULTS

switch. Except for the receptacle times the times are not significantly (statistically) different; they may be lumped together in the average contact time shown in Table 4. Receptacle times may be longer because they include 3 mm of travel at close tolerance. Contact times are simply processing times required to assure the operator that the contact was indeed made.

Table 4

GRASP AND RELEASE TIMES IN SECONDS FOR EACH SUBJECT

	Grasp		Release		Contact	
	Subj. 1	Subj. 2	Subj. 1	Subj. 2	Subj. 1	Subj. 2
Hand	0.20	0.20	0.40	0.35	.35	.28
Model R	2.56	3.04	1.92	1.88	.40	.83
Ames	4.60	7.36	2.88	2.76	.39	.85

V DISCUSSION OF RESULTS AND CONCLUSIONS

Experimental results in this form provide a unique way of comparing manipulators, force feedback conditions, viewing conditions, controller displays, subjects, etc. The unit motion elements offer a microscopic look at results compared to overall task times that previous experiments have measured.

A. Performance with Different Force Feedback Conditions

Comparative performance with different force feedback conditions can be evaluated by using the data from the unit motion elements involving force (or contact with the environment). These elements do not involve rapid motions and hence are not limited by the manipulator. Crank and turn (Figures 6 and 7) reveal that these operations are twice as fast when force feedback is present. Similarly, low-tolerance disengage (Figure 5) is drastically slowed with no force feedback. Surprisingly, inserting (Figure 4) shows little difference with or without force feedback.

B. Performance with Different Manipulators

Performance with different manipulators is best compared using position and move (Figures 8 and 9). These elements do not involve contact, so force is not a factor. They do, however, permit comparison of both speed and accuracy. Positioning times for the two manipulators are very similar, except for the lowest tolerances -- in which case the Ames Arm is slower. Moving times for the Ames Arm are consistently 20% longer than for Model H. This discrepancy is probably due to the rate limits on the Ames Arm servos.

C. Task Modeling and Prediction

Modeling of a manipulation task conforms to the same rules of industrial time and motion studies. Literature describing several systems has been cited in Section II. Once the task has been broken down into its basic elements, times for these elements are obtained from the graphs (Figures 4 to Figures 9) and Table 4. The unit times are totaled to obtain the predicted task time.

An example of this procedure for the pick-and-place task is given in Table 5. Separate results are presented for each subject and manipulator to illustrate the variation that may be expected in each case.

Table 5

MODEL VERIFICATION FOR PICK-AND-PLACE TASK (Times in Seconds)

Basic Element	Hand Subj. 1	Hand Subj. 2	Model H Subj. 1	Model H Subj. 2	Ames Subj. 1	Ames Subj. 2
Contact	.35	.28	.40	.83	.39	.85
Move(250)	.44	.50	1.08	1.24	1.34	1.28
Grasp	.20	.20	2.56	3.04	4.60	7.36
Move(250)	.44	.50	1.08	1.24	1.34	1.28
Prepos.(38)	.00	0.00	0.11	0.18	0.11	.22
Contact	.35	.28	.40	.83	.39	.85
Move(250)	.44	.50	1.08	1.24	1.34	1.28
Prepos.(51)	.00	0.00	0.08	0.20	.16	.22
Release	.40	.35	1.92	1.88	2.88	2.76
Move(250)	.44	.50	1.08	1.24	1.34	1.28
Prepos.(25)	.10	0.06	0.40	0.48	.35	.64
Element Total Time	3.16	3.17	10.19	12.40	14.24	18.02
Actual Total Time	4.04	3.36	8.96	13.16	17.92	18.52
Difference	-.88	-.19	1.23	-.76	-3.68	-.50
% of Difference	-22%	-6%	14%	-6%	-20%	-3%

There is a considerable disparity between individual subjects (47 percent for the Model H arm) that must be taken into account. With the limited data (two subjects) available from these experiments, no average unit times would be meaningful. This is the reason the two subjects are individually tabulated in Table 5. The unit motion model predicts the results of the experiment to within 20%. The author believes the main reasons for the difference between element total and the actual total times are the small amount of data acquired (with 100 repetitions instead of 6 the actual times would have been more uniform).

Industrial time and motion studies like MTM, which are based on a substantial population of workers, have introduced additive and multiplicative factors to adapt population mean unit times to a particular worker's motivation, size, and ability. These factors are outside the scope of our preliminary study. The difference between the two subjects operating each of the manipulators may be taken as an indication of the range of results obtainable. After a subject has had considerable practice using a manipulator, the unit times may be reduced and become more repeatable from one individual to another.

VI RECOMMENDATIONS

In this study we show how a slightly modified version of the industrial time and motion systems can be extended to remote manipulators. As described in Section II of this report, the unit motion breakdown can be valuable in planning and optimizing tasks. Because of the potential benefits to be realized in planning remote manipulation facilities and optimizing tasks for future missions, it is recommended that NASA continue to pursue the time-and-motion approach to modeling manipulator performance. Methods for performing future missions could be developed and timed in advance and necessary equipment specified and budgeted without expensive design studies.

Furthermore, the unit element approach to modeling task performance is seen to have application in other portions of the remote manipulation tasks. Areas of application include:

- Remote viewing
- Controls
- Information displays
- Supervisory control
- Manipulator design.

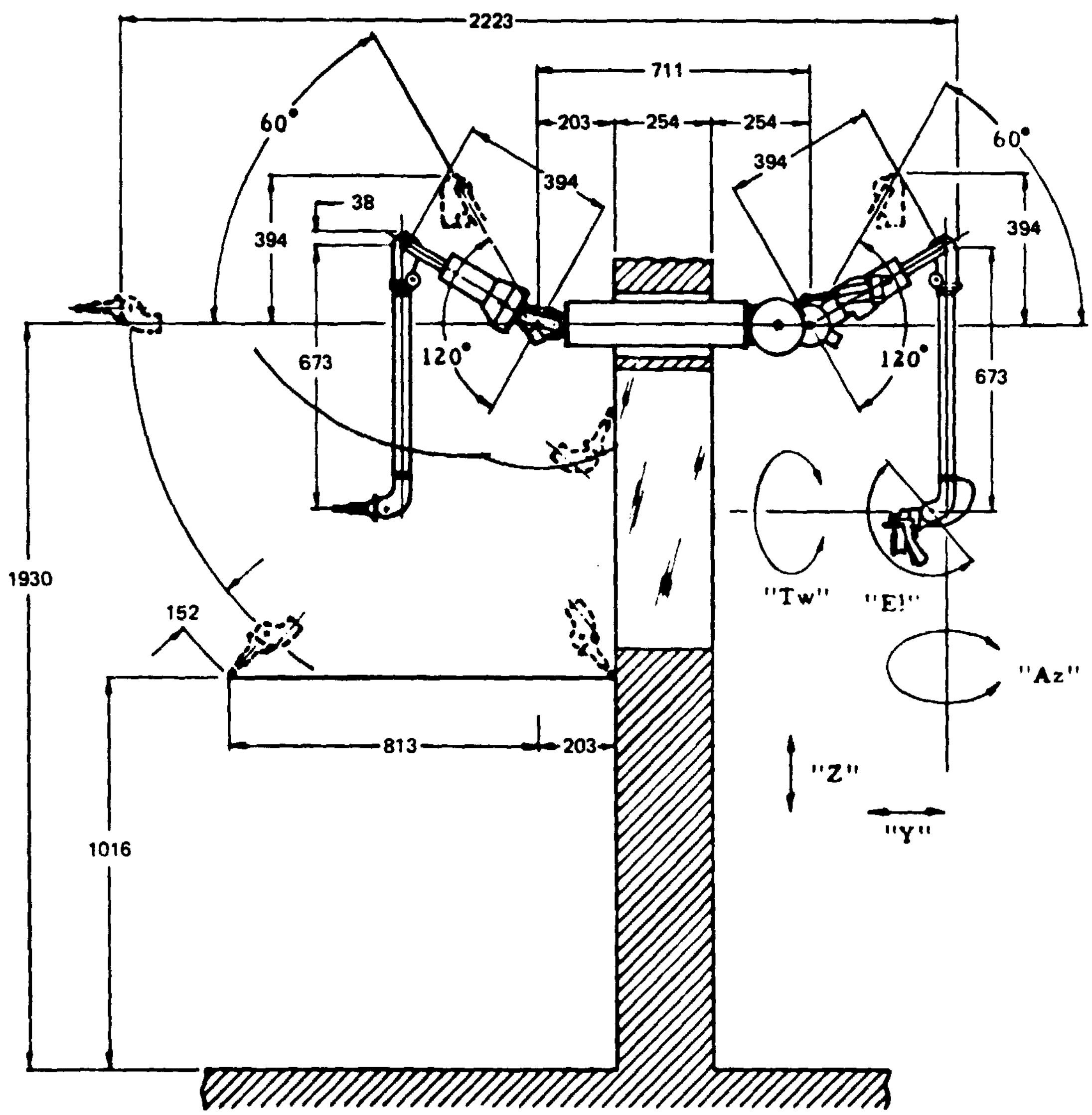
For example, times for elemental motions with stereo displays may be contrasted with those obtained in mono TV viewing; joysticks with control braces; proportional displays with numeric; automatic with manual operations; and one manipulator with another. In addition to the analytical value of these measures for comparison, they would have considerable predictive and planning value for future missions.

VII NEW TECHNOLOGY

No reportable items of new technology have been identified.

Appendix A

DIAGRAM OF THE MODEL H MANIPULATOR



Dimensions in millimeters

FIGURE A-1 SIDE VIEW OF MODEL H MANIPULATOR

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