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STUDY TO DESIGN AND DEVELOP REMOTE MANIPULATOR SYSTEMS

Annual Report 2
Covering the Period 1 August 1976 to 30 November 1977

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Prepared for:

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ABSTRACT

This report describes part of a continuing effort both to develop models for and to augment the performance of humans controlling remote manipulators. The project plan calls for the performance of several standard tasks with a number of different manipulators, controls, and viewing conditions, using an automated performance measuring system; in addition, the project plan calls for the development of a force-reflecting joystick and supervisory display system.

Two experiments with different approaches to varying the difficulty of the task have been devised: a peg-in-hole task and a variable degree-of-freedom task. The first uses precision of fit to vary the difficulty while maintaining four degrees of constraint; the second uses a nearly constant precision but uses the number of degrees of constrained motion to control the difficulty.

Experiments with a cable-connected master-slave manipulator (the MA-11) common to hot cell work have been carried out with both tasks and are reported here as are experiments with a servo-controlled manipulator (the MA-23) with and without force feedback. Four experiments with the Ames Arm to evaluate four different viewing systems (including stereo and head-aimed stereo displays) were run.

To facilitate man-manipulator interaction, two approaches have been explored: a force-reflecting control stick and a real-time supervisory display concept. The control stick has two primary functions: sensing position and applying forces. It permits the monitoring of both position and orientation as well as the application of both forces and torques to the operator's hand. The desk-top design permits him to control a six-axis manipulator and feel the forces it develops. The computer controlled display can show the operator how the remote manipulator and its remote sensors are performing in a single graphic image. Software to interact with the system via the keyboard and the force-reflecting controller

has been developed. Perspective displays of three-dimensional objects can be moved by the controller, as can numeric and analogic displays.

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ILLUSTRATIONS

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I INTRODUCTION

A. Performance Evaluation

The first part of this report describes a series of experiments to develop models for human performance with remote manipulators. The project plan calls for the performance of standard tasks with a number of different manipulators, controls, and viewing conditions, using an automated performance measuring system. Specifically this report describes two tasks--the performance measuring system and the preliminary results of experiments with two manipulators. This work is a continuation of the first annual report[1*] under Contract NAS2-8652.

The performance measuring system described in Section II uses a tensioned string to measure the distance between the tip of a tool and a receptacle into which the tool is to be inserted. The string also permits the progress into the hole to be monitored as the tool is inserted. From records of string length as a function of time, tool trajectories as well as velocities and task times can be determined. The system makes a permanent record of the string length 25 times a second as the tool is moved to and into the receptacle.

The tasks are the degree-of-constraint experiment described in the first annual report on this project[1] and the peg-in-hole experiment of McGovern.[2] The experiment boards have been rebuilt to be more precise and to be incorporated into the measuring system. Both experiments have been expanded to use three different moving distances (100, 200, and 400 mm) to provide a broader data base for the models. Both are performed by the same subjects to make the results comparable.

The first of two manipulators chosen for these experiments was the French MA-11. The MA-11 is a lightweight cable-connected manipulator designed for hot cell work. It is similar to the Model 8 developed at

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[*] References appear on page 113.

Argonne Labs and is representative of a large class of manipulators in use throughout the world in radioactive environments. Since there are thousands of these cable-connected manipulators in use in the world, they provide a standard for comparison with other types of manipulators. They provide the operator with a low mass (5 kg) manipulation link to tasks with only six degrees of freedom. This link essentially removes the enormous dexterity and tactile sensibility of the human hand and limits the operator to motion and sensing with the six degrees of freedom provided.

The second manipulator chosen was the MA-23 force-reflecting servo manipulator developed by the French Atomic Energy Commission (CEA). This manipulator system may be run with force feedback turned either on or off. It is one of a handful in the world with this feature. An attempt was made to run the experiments with a similar American manipulator, the E-4 manipulator at Fermi National Accelerator Laboratory, Batavia, Illinois, but it was not operational at the time scheduled for the experiment. Manipulators with force feedback capability were sought to characterize the changes in performance attributable to force feedback.

Sections III and IV describe analyses of the data. Computer programs for determining task time and time for movement of a given distance to the receptacle have been developed. Results of these programs are used to automatically plot several graphs presenting the data. Task times, accumulated distance, and trajectories showing the distance from the receptacle as a function of time are presented in these sections. Statistical tests on the results are described in Section V. This work has been summarized in a paper presented to the Thirteenth Annual Conference on Manual Control (Appendix A).

Additional experiments to explore the effects of other manipulators and viewing situations have been carried out but not analyzed. Experiments with the Ames manipulator and unaided human hand were carried out at Ames Research Center to determine the effect of viewing systems on experimental results. The peg-in-hole tests run with direct viewing, TV viewing, stereo TV viewing, and the head-aimed viewing system developed at Ames Research Center are described in Section VI.

B. Supervisory Control System

The second part of this report describes the initial developments of a second-generation control system for remote manipulators. The control system consists of the force-reflecting control stick, described in Section VII, and a graphics terminal for "looking" into the operations of the system, described in Section VIII.

The force-reflecting controller permits free motion of the operator's hand in a working volume 30 cm on a side. An articulated set of linkages measures the position (X, Y, and Z) and orientation (roll, pitch, and yaw) of a grip held in the operator's hand. By means of flexible cables, each of the linkages is back-driven to apply forces along the X, Y, and Z axes and torques around the roll, pitch, and yaw axes. In the case of manipulation, the controller can be a force-reflecting master. Other applications include vehicle control, tracking, man-machine interaction with a data base, and instructional uses. When the controller is interfaced to a computer, there are several new possibilities for simulation and interaction using modeling techniques.

The graphics terminal is a GT-40 manufactured by the Digital Equipment Corporation. Software for the terminal permits the human operator to quickly review, through position, velocity, force, tactile, and other sensors, a variety of visual data presentations concerning a manipulator's performance. Entire display modules (computer programs) are down-loaded from the KL-10 host time-sharing computer in a few seconds. The modules convert the incoming analog sensor data into graphic form and provide supporting displays of textual, numeric, and analogic information. At the bottom of the display screen is a permanent "teletype window" that permits simultaneous interaction between the operator, the graphics terminal, and the host computer(s).

II PORTABLE DATATAKER

A portable data collection system was designed and constructed to obtain and compare performance of different teleoperators. The system measures the distance from a tool to a receptacle in which the tool is to be inserted. The datataker records the distance between the end of the tool and the bottom of the receptacle as a function of time. This distance is measured by a dacron string of low extensibility to the nearest 2 mm and is punched on paper tape at the rate of 25 measurements/sec. The range is calibrated from 0 to 510 mm in 256 steps (8 bits).

The entire experimental arrangement is shown in Figure 1. The experimenter operates the tape perforator at the left, while the subject manipulates the tool held on the right. The measuring string connects the tool and the string puller. Details of the string dispenser and measuring system are shown in Figure 2. This system is similar to that previously described[1] for measuring the X, Y, and Z coordinates of the manipulated tool, except that a single string is used. This simplification in measuring was suggested by the results of two previous studies using a more sophisticated datataker.[2,3] In these studies the distance between hole and tool as a function of time was the most important parameter in explaining the experimental results. This measurement could be used to divide the task into different therbligs and to proportion a fixed amount of time for each one.

The new datataker is well-adapted to the Ames Arm and other rigid manipulators that tend to bump the task board and move it around. In this case the measuring system is located inside the task board, and even if it is moved the origin remains the same.

Details of the measuring unit are shown in Figures 3 and 4. There are four sets of receptacles for the unit: one round hole in a metal plate for the peg-in-hole task and three irregular-shaped holes for the

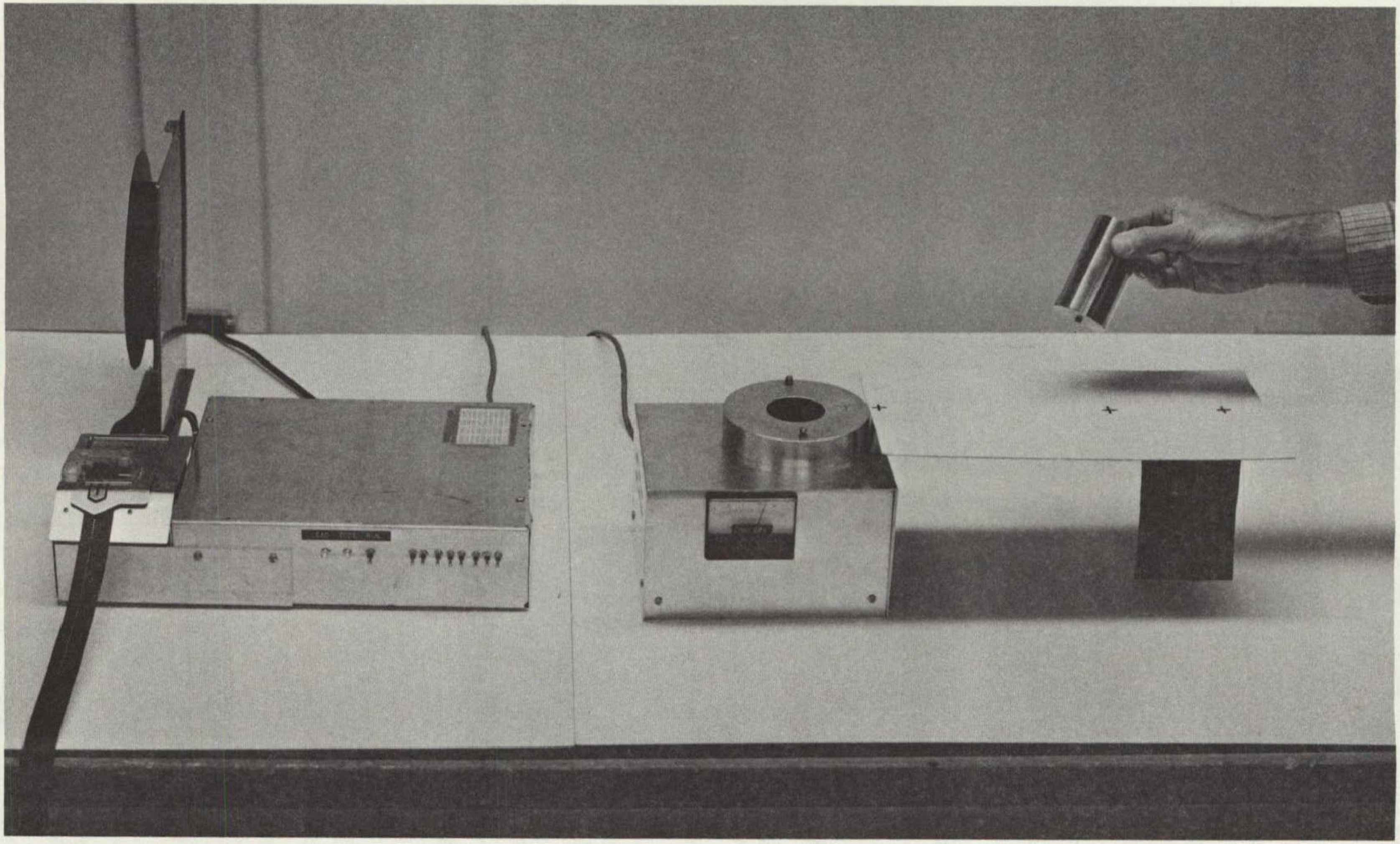

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FIGURE 1 DATA RECORDING UNIT AND MEASURING UNIT

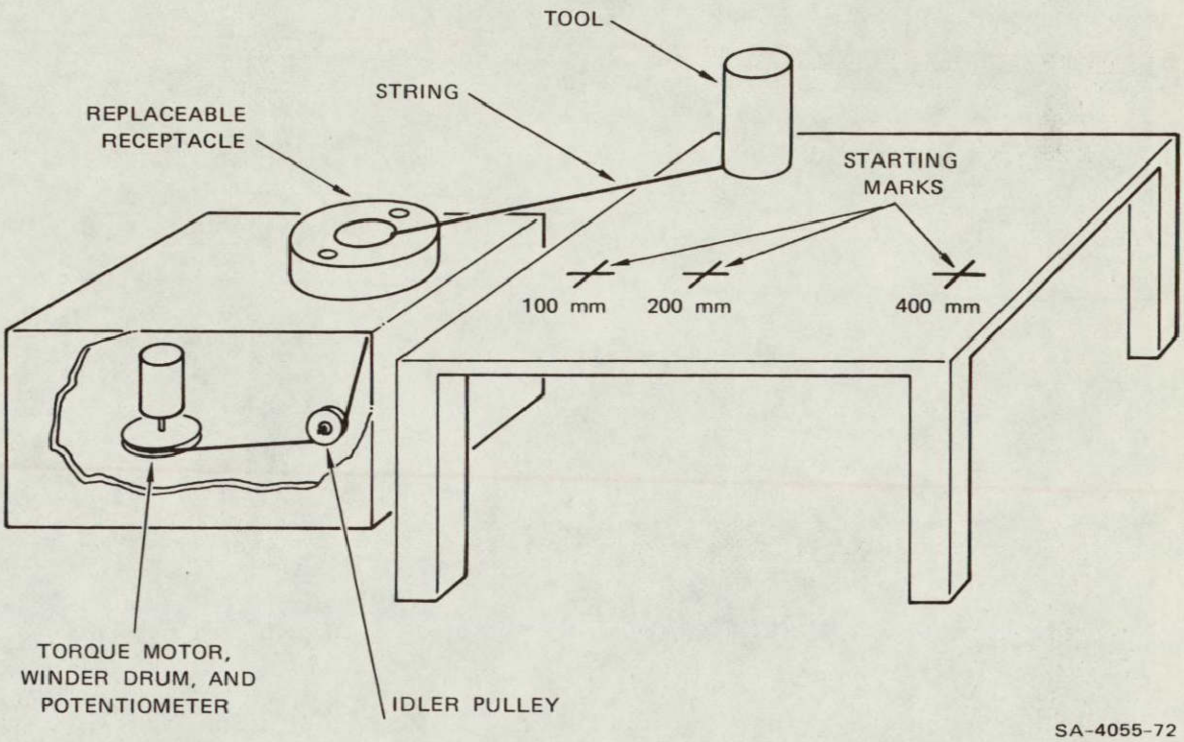

FIGURE 2 TASK CONFIGURATION WITH MEASURING UNIT AND ACCESSORY TABLE

degree-of-constraint experiment. The use of these receptacles is described in the parts of the report dealing with the individual experiments.

A. Operation of the Datataker

The block diagram of the tape perforator is shown in Figure 5. The unit is operated by a set of switches. Trajectories are punched by lifting the DATA switch; the 8-bit code set on the code switches is punched by momentarily pressing the CODE pushbutton; and blank leader to separate codes and trajectories is punched by momentarily pressing the LEADER switch.

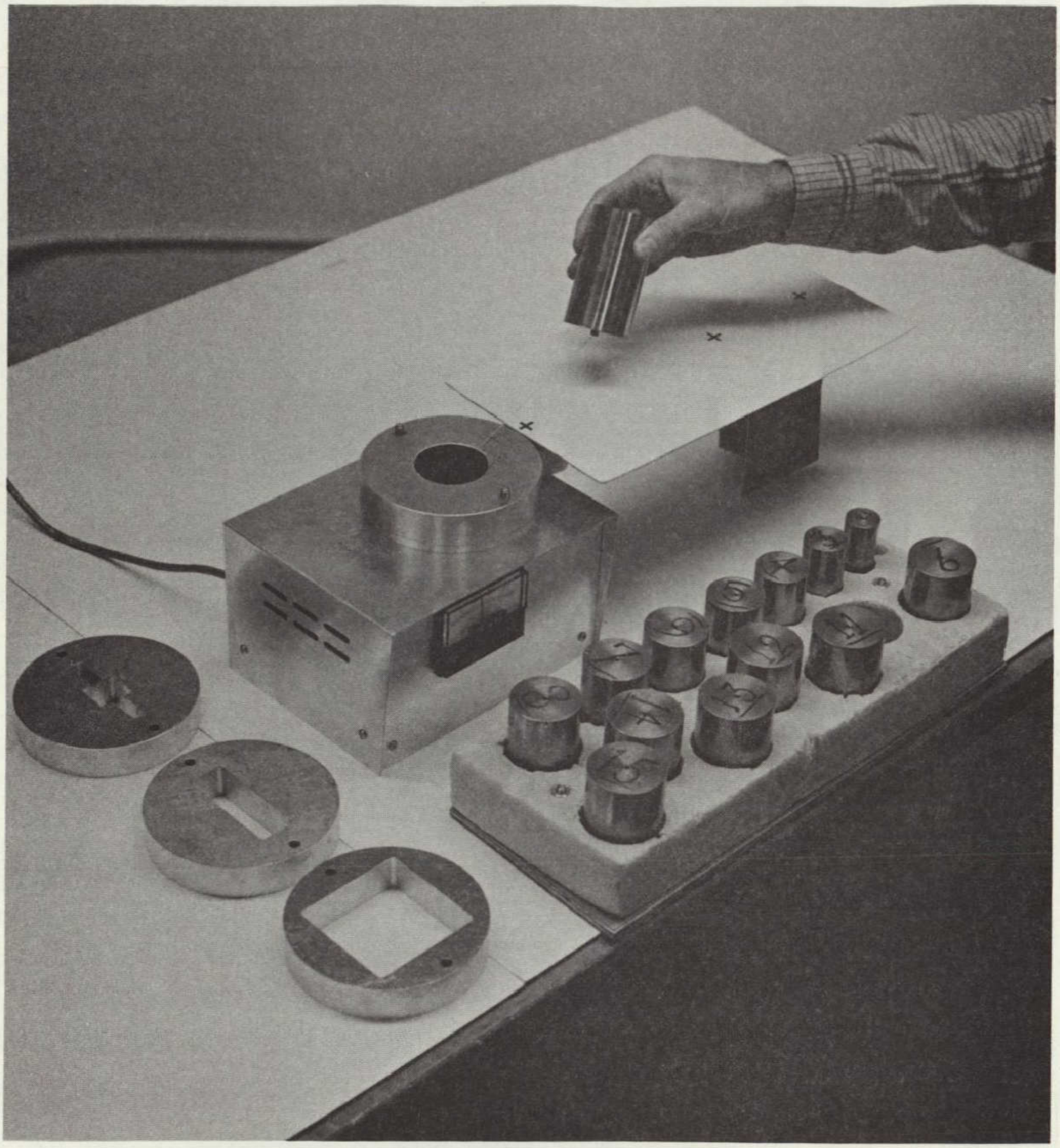

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FIGURE 3 MEASURING UNIT SHOWING SET OF RECEPTACLES AND PEGS

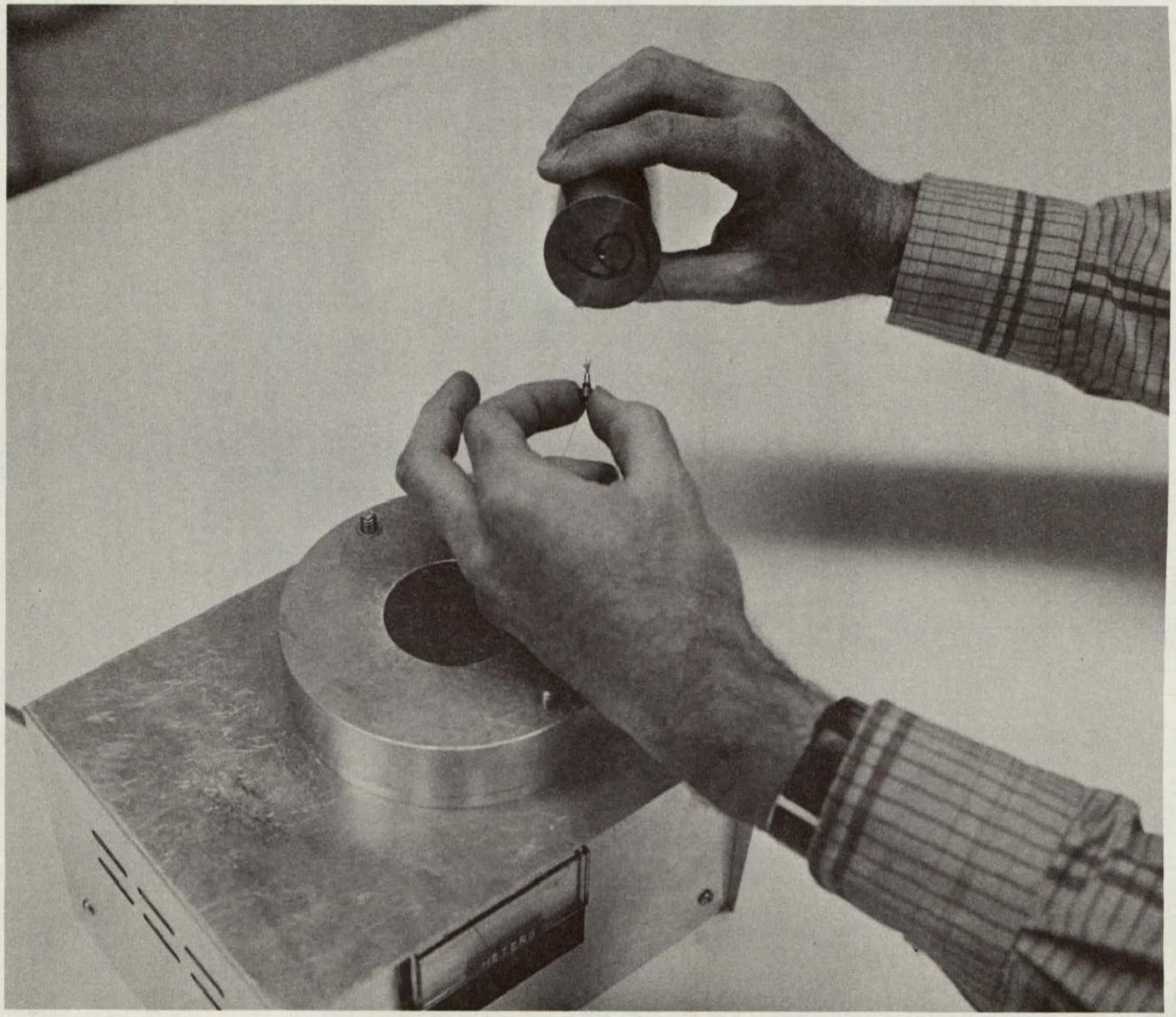

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FIGURE 4 DETAIL OF TOOL CHANGE

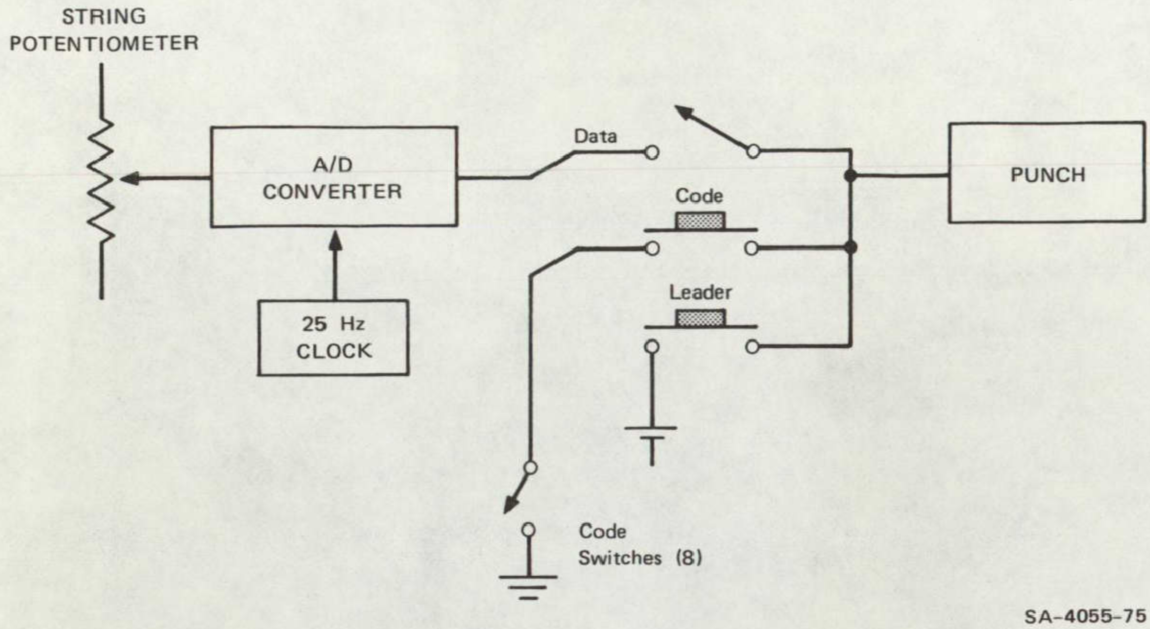

FIGURE 5 BLOCK DIAGRAM OF DATATAKER

Codes used to identify different parts of the experiment are indicated below (numbers are in octal):

Identification Code	Definition
Experiment identification	300 + experiment number
Subject identification	200 + subject number
Condition identification	100 + distance code + condition code
Distance code	0, 20, 40 for identifying the 100, 200, 400 mm starting distances, respectively
Condition code	A number between 0 and 17 for identifying the peg used or degrees of constraint used
Run identifcation	A number between 1 and 77 increasing by 1 for each repeated trajectory

The rules for recording identification codes follow:

(1) Blank leader is used to separate each code and trajectory recording.

(2) Codes are recorded only when a change occurs.

For example, only when Subject 3 starts manipulating is the code 203 punched. Similarly, only when Experiment 1 begins is 301 punched, and only for the first insertion is the two-part condition identification punched. Before each insertion a consecutive run identification number is punched (1, 2, 3, 4, and so forth). Repeating the run identification number in this fashion permits a run to be repeated if a difficulty develops: when two Run 2s are recorded in sequence, the first punched data are to be disregarded and the second data kept for Run 2.

The length of the string is calibrated at the beginning of the experiment and whenever the string breaks or is replaced. Calibration is done in the following manner: the tip of the tool being used is placed flush with the top of the receptacle (defining the entrance to the hole as zero distance), and the number 300 (Experiment 0) and the string length are punched. This is done by setting 300 on the switches and briefly pressing the LEADER, CODE, LEADER, and DATA buttons in that sequence.

B. Computer Processing of Paper Tape

Integral to the data punching scheme just outlined is the computer processing scheme for reducing the data. Both must use the same rules. In addition to keeping track of the various codes for each manipulation, the data reduction program given in Appendix B also makes a set of measurements on the trajectories. A sample of the measurements is shown in Figure 6; they represent some of those made by the program.

The measurements made by the program are briefly described below:

Reaction Time--Reaction time is the time after the experimenter turns on the punch, which is the audible signal for the subject to begin, until the subject pulls the string 4 mm from its initial length (time zero).

Zero Length--Zero length is the string length when the tool is at the entrance to the receptacle. This length is determined from the calibration recordings (Experiment 300).

Start Distance--Start distance is the difference between the string distance at time zero and zero length, as defined above.

Task Time--Task time is the time from when the tool is first moved until it has been inserted 25 mm into the receptacle.

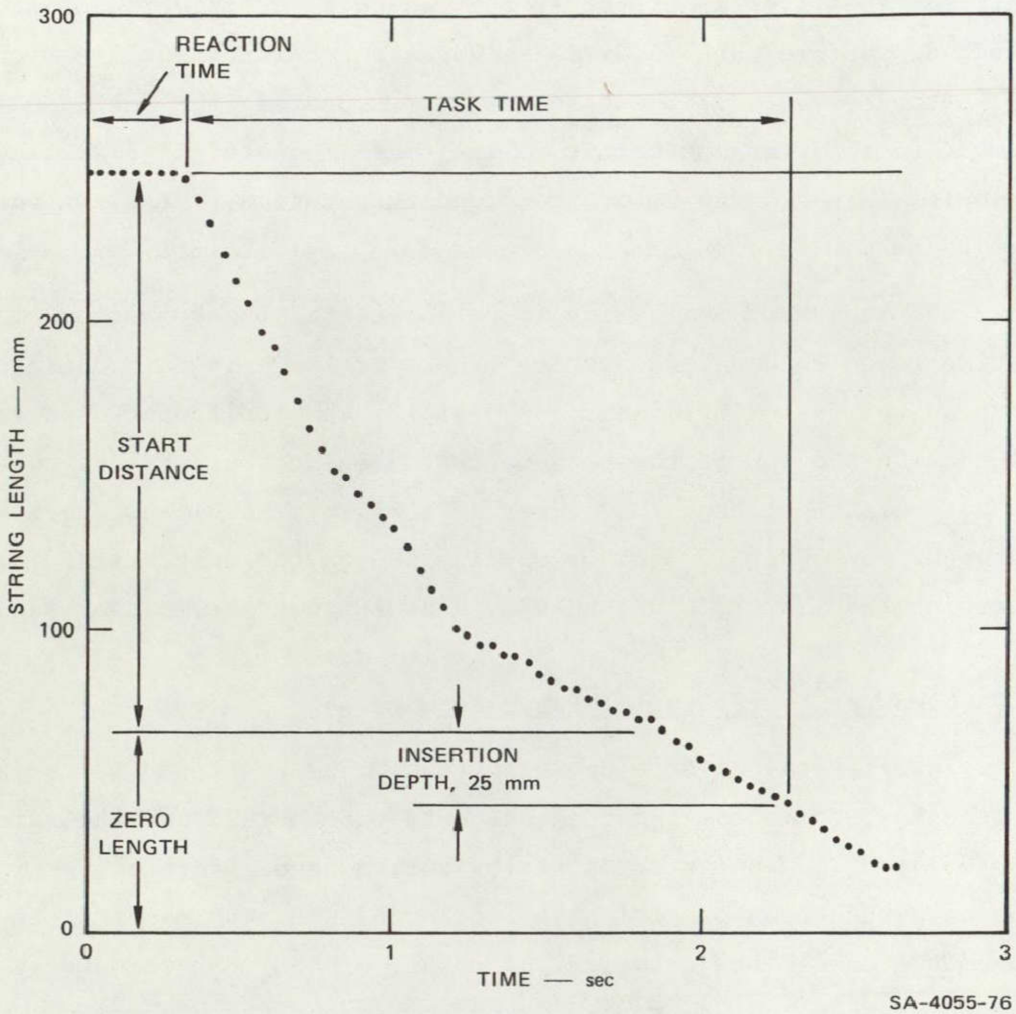

FIGURE 6 SAMPLE TRAJECTORY MEASURED BY DATATAKER

In addition to these parameters, the first times to a set of given distances from the hole entrance are determined in order to plot the average trajectory. The set of distances are: 350, 300, 250, 200, 150, 100, 90, 80, 70, 60, 50, 40, 30, 20, 10, and 0 mm from the hole and 10, 20, 25, and 30 mm into the hole.

III DEGREE-OF-CONSTRAINT EXPERIMENT

The degree-of-constraint (DOC) experiment was carried out with the task board previously described and a set of special tools. The task consists of moving a previously grasped tool a fixed distance and inserting it into a receptacle. The tools and receptacles were designed to constrain the translational and rotational movements of the fitting task one by one, making the task progressively more difficult. Tool trajectories were recorded as a function of time, using the data acquisition system described in Section II.

A. Apparatus

The matching of the receptacles and tools for the six tasks is illustrated in Figure 7. Dimensions for the set of four tools and three receptacles are given in Appendix C. The tools are held, around their cylindrical handles, in the jaws of the manipulator. The grip is secured by a small C-clamp to ensure that the tool does not slip in the jaws.

B. Manipulators

Two different manipulators were chosen for use in the experiment: a lightweight master-slave manipulator (MA-11) of the family used for hot cells and a heavy duty servo manipulator (MA-23) that has more general-purpose use. These manipulators are shown in Figures 8 and 9. Technical descriptions including dimensions, load capability, speed, and backlash for the MA-11 and MA-23, respectively, are given in Appendices D and E. Both manipulators were developed by the French Atomic Energy Commission at Saclay, France, for radioactive handling by Dr. Jean Vertut's Environmental Protection group. The relation between the subject and the task boards is shown in Figures 10a and 10b.

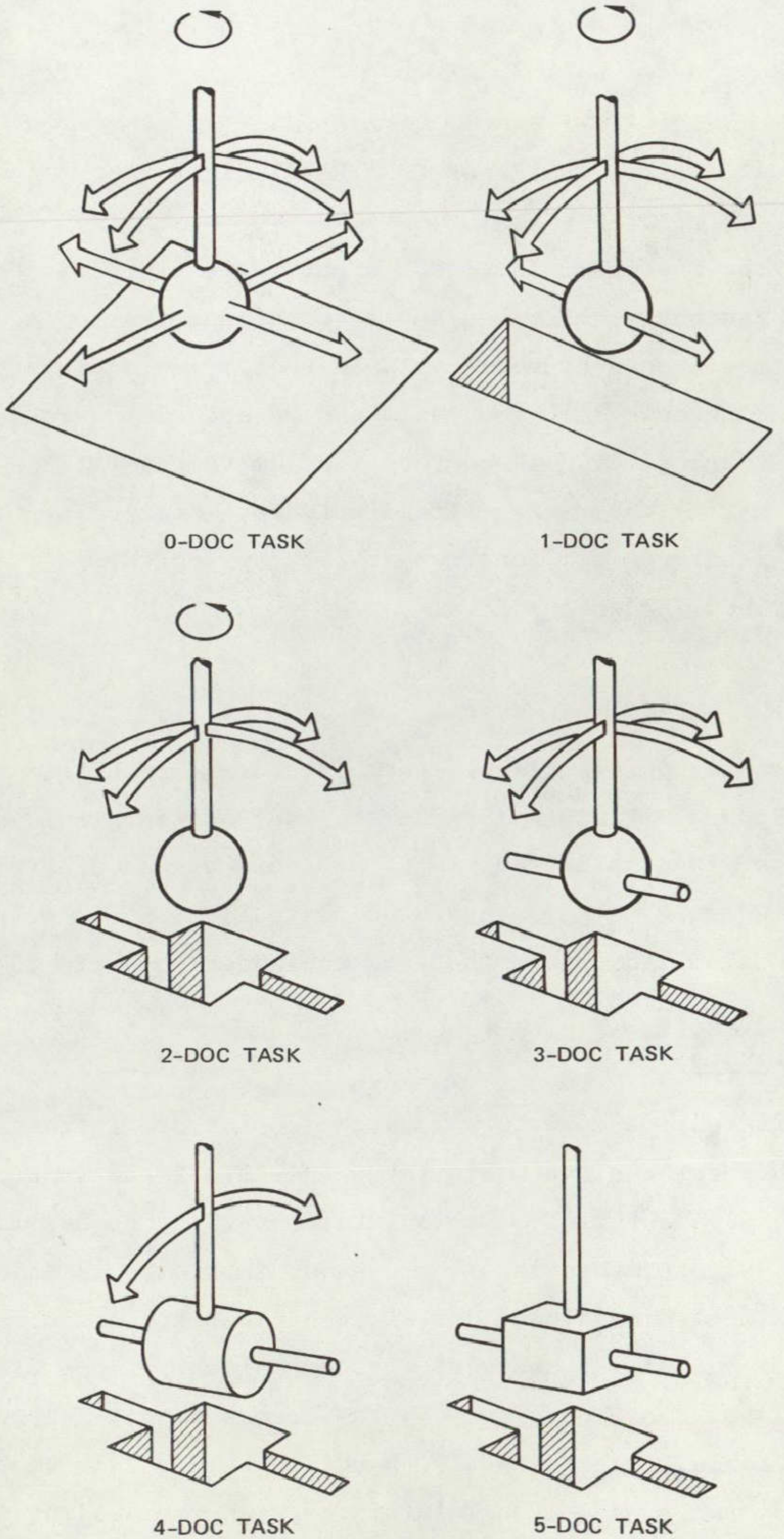

FIGURE 7 SIX TASKS FITTING TOOLS INTO RECEPTACLES

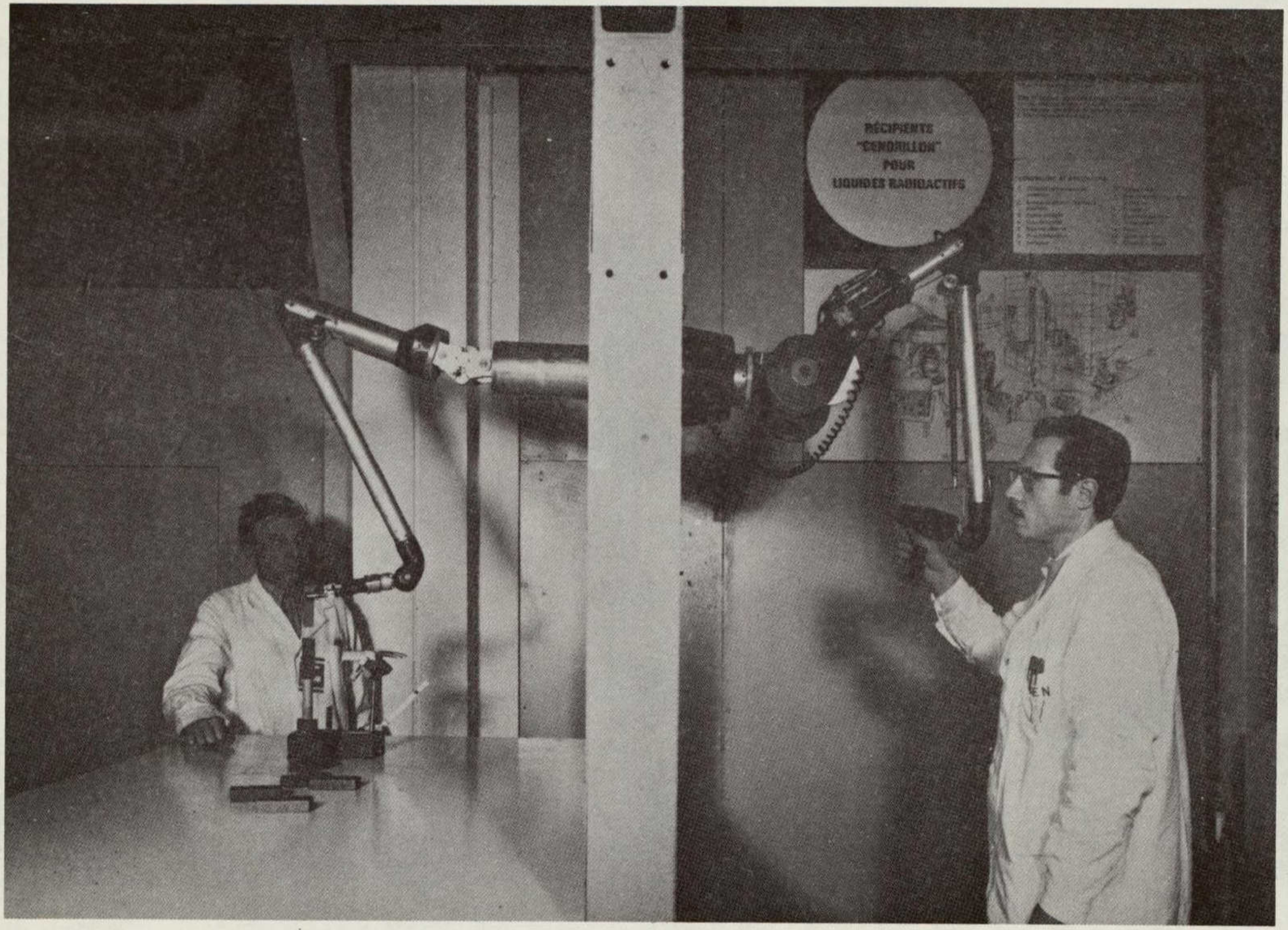

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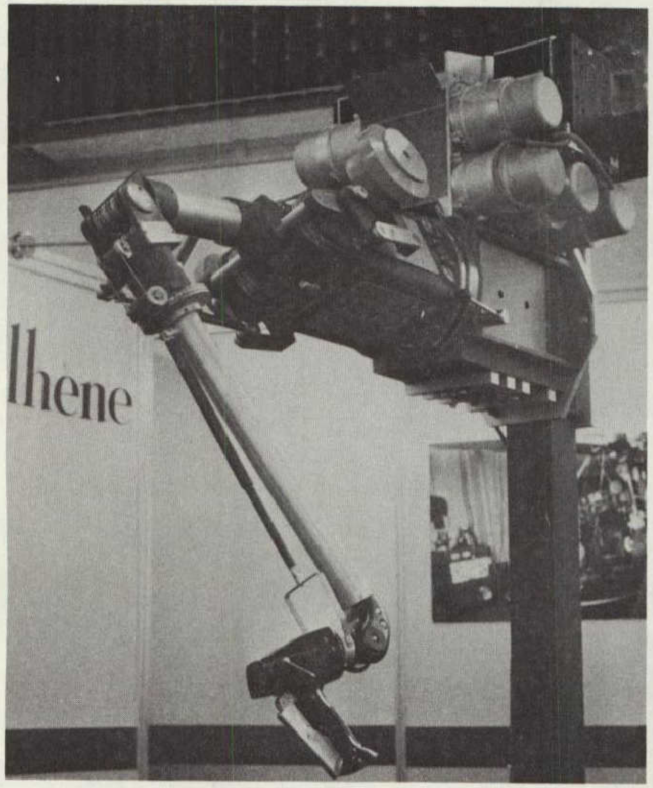
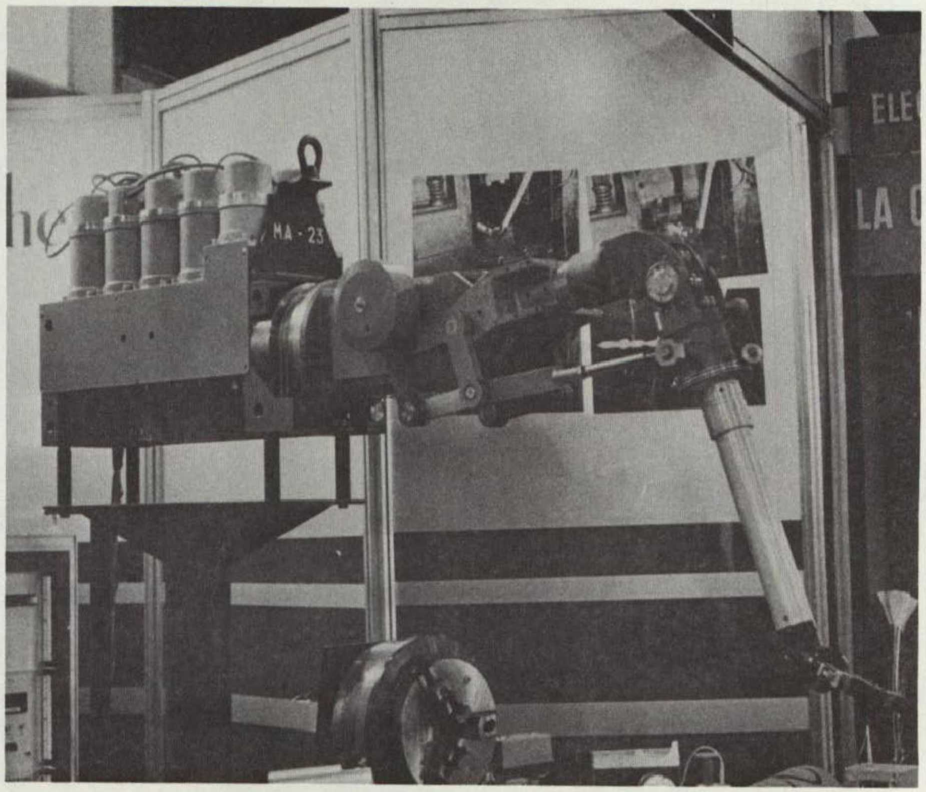
FIGURE 8 MA-11 CABLE-CONNECTED MASTER-SLAVE MANIPULATOR



(a) MA-23 FORCE-REFLECTING MASTER (5 kg)



(b) MA-23/200 HEAVY DUTY SLAVE (25 kg)

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FIGURE 9 MA-23 SERVOMANIPULATOR

C. Experimental Design

The basic experiment consists of the 6 X 3 X 8 factorial design shown in Figure 11. The experiment block was run in the sequential order shown in Table 1 for one subject and in the reverse order for a second subject, to balance the effect of learning curves on the results. For each of the distance and DOC combinations of Table 1, eight insertions of the tool into the receptacle were made.

This design is similar to that previously used,[1] except that three distances, 100, 200, and 400 mm, are used instead of the single distance (490 mm) previously used. These distances are chosen to be the same as those of the peg-in-hole experiment. They also increase by multiples of two for convenience of using and testing Fitts' law.[4]

D. Procedure

The experimental protocol was as follows: for each of the sequential conditions called out in Table 1, a new tool, if called for, was rigidly fixed inside the manipulator jaws by means of a small C-clamp. A new receptacle, if called for, was mounted on top of the measuring unit. The subject was permitted to make a few practice movements, and, if a new tool or receptacle were being introduced for the first time, the subject was encouraged to practice a few times. For each of the eight repeated insertions, the subject positioned the tip of the tool over the appropriate starting mark (100, 200, or 400 mm). The experimenter punched the run number, waited a second or two, and switched on the punch, which made a distinct noise. When the subject heard the noise, he proceeded to move the tool into the receptacle. When the tool tip disappeared inside the receptacle (about 50 mm) the experimenter turned off the punch and the subject returned the tool to the starting mark to prepare for the next insertion.

E. MA-11 Preliminary Results

The DOC experiment was run with two subjects in the manner previously described and the resulting trajectories treated by computer program to

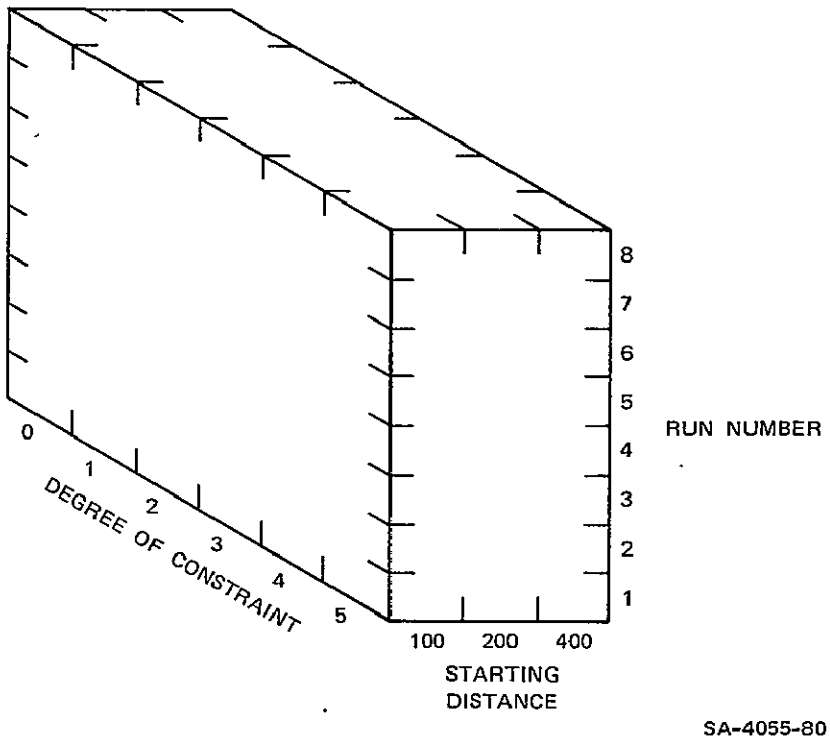


FIGURE 11 DEGREE-OF-CONSTRAINT EXPERIMENTAL DESIGN

obtain task times and details on the trajectories. The data reduction was automated in view of the large number of manipulators and experimental conditions to be compared in the research program.

As described earlier, task completion time is the time from the beginning of the move until the tip of the tool is inserted 25 mm into the receptacle. At this point the tool is half way into the receptacle, and the angular and translational degrees of freedom are constrained as determined by the geometry of the tool and receptacle. Averaged task times for the two subjects are shown in Figure 12. These task times increase regularly with DOC, as was observed in previous experiments.[3] This is true for all three trajectory lengths. The previous experiments used only one trajectory length, and further comparison cannot be made.

Approach times to different distances to the receptacle were obtained and are shown in Figure 13. The time to a given distance is defined as

Table 1

ORDER OF TASKS USED IN
THE DEGREE-OF-CONSTRAINT EXPERIMENT

Order	Degrees of Constraint	Distance (mm)	Octal Condition ID
1	0	100	100
2	0	200	120
3	0	400	140
4	1	400	141
5	1	200	121
6	1	100	101
7	2	100	102
8	2	200	122
9	2	400	142
10	3	400	143
11	3	200	123
12	3	100	103
13	4	100	104
14	4	200	124
15	4	400	144
16	5	400	145
17	5	200	125
18	5	100	105

the time from the beginning of the move to the first time the string length is less than the given distance. Data are average times for eight runs each from two subjects. The figure's curves show an increase in time spent close to the receptacle with the larger number of degrees of constraint. The amount of time needed to move between 0 and 20 mm into the hole (0 mm and 20 mm in Figure 13) depends on the trajectory length as well as the DOC. The curves for the 100-mm trajectory are accelerating functions and those of the 400-mm trajectories are decelerating functions of the DOC. Previous experiments have assumed that the inserting times are not a function of trajectory length.

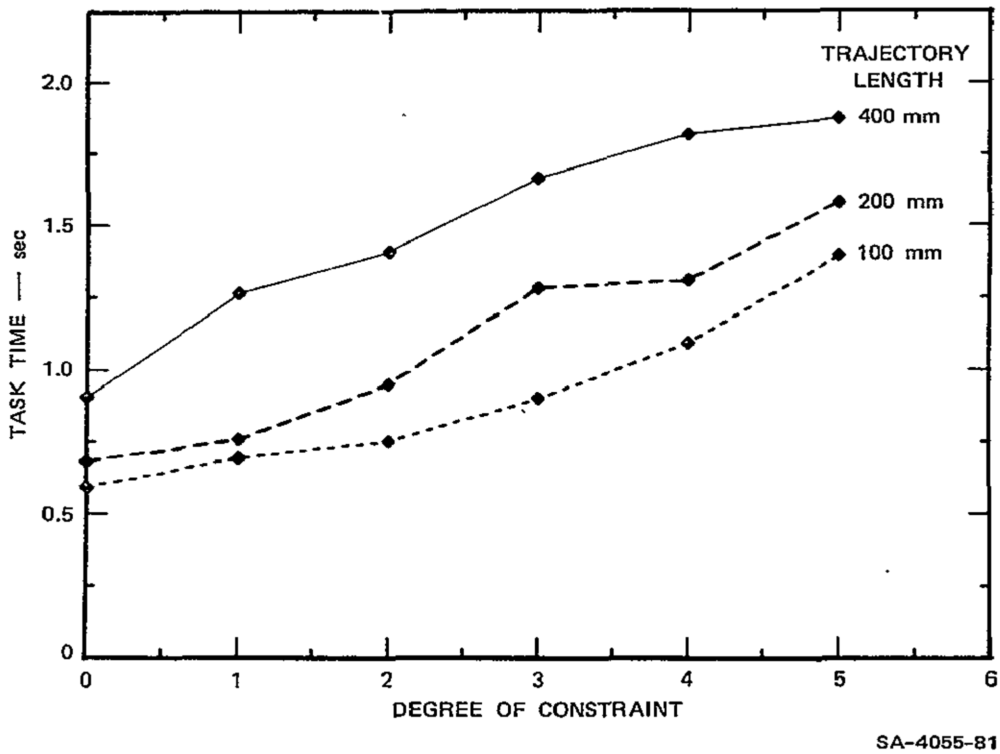


FIGURE 12 MA-11 TASK COMPLETION TIMES

Trajectories for the 0, 2, and 4 DOC insertions are shown in Figure 14. These are averaged trajectories, indicating the first time that a given approach distance was realized. They are averaged over eight runs each from two subjects. The curves show the transition from the differing initial velocities with different starting distances from the hole to nearly identical behavior when in proximity of the hole. As the degree of constraint increases, the curves at zero distance steepen, indicating the increased difficulty in fitting the tool. On each of the three graphs in Figure 14, the three curves have the same shape near the origin, suggesting that the fitting task is independent of initial trajectory length.

F. Preliminary Comparison of MA-23 With and Without Force Feedback

In part of a program to determine the advantages of force feedback in different manipulation tasks, the DOC task was run on an MA-23 manipulator with and without force feedback. The comparison was made with two

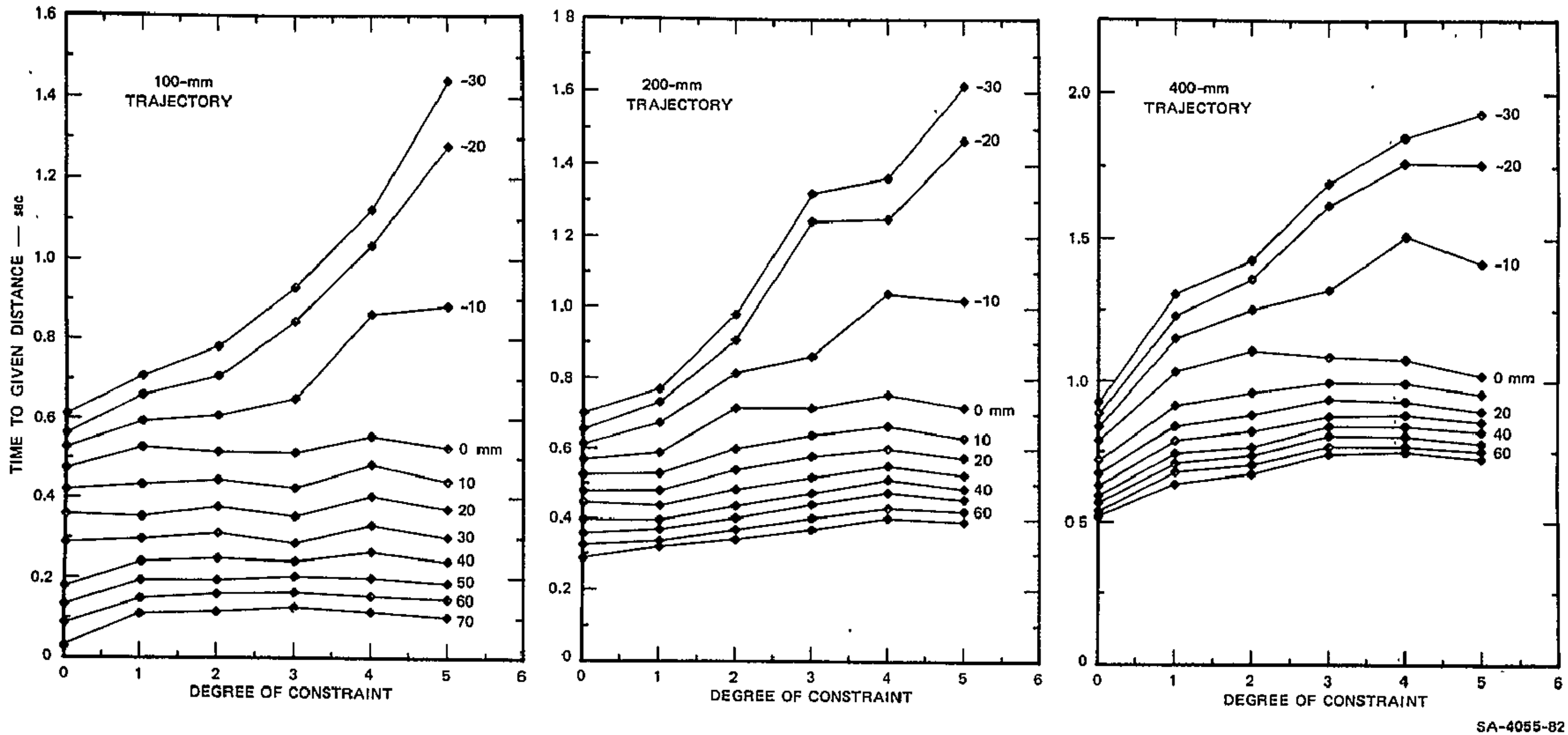


FIGURE 13 MA-11 APPROACH TIMES FOR DIFFERENT DISTANCES TO THE RECEPTACLE

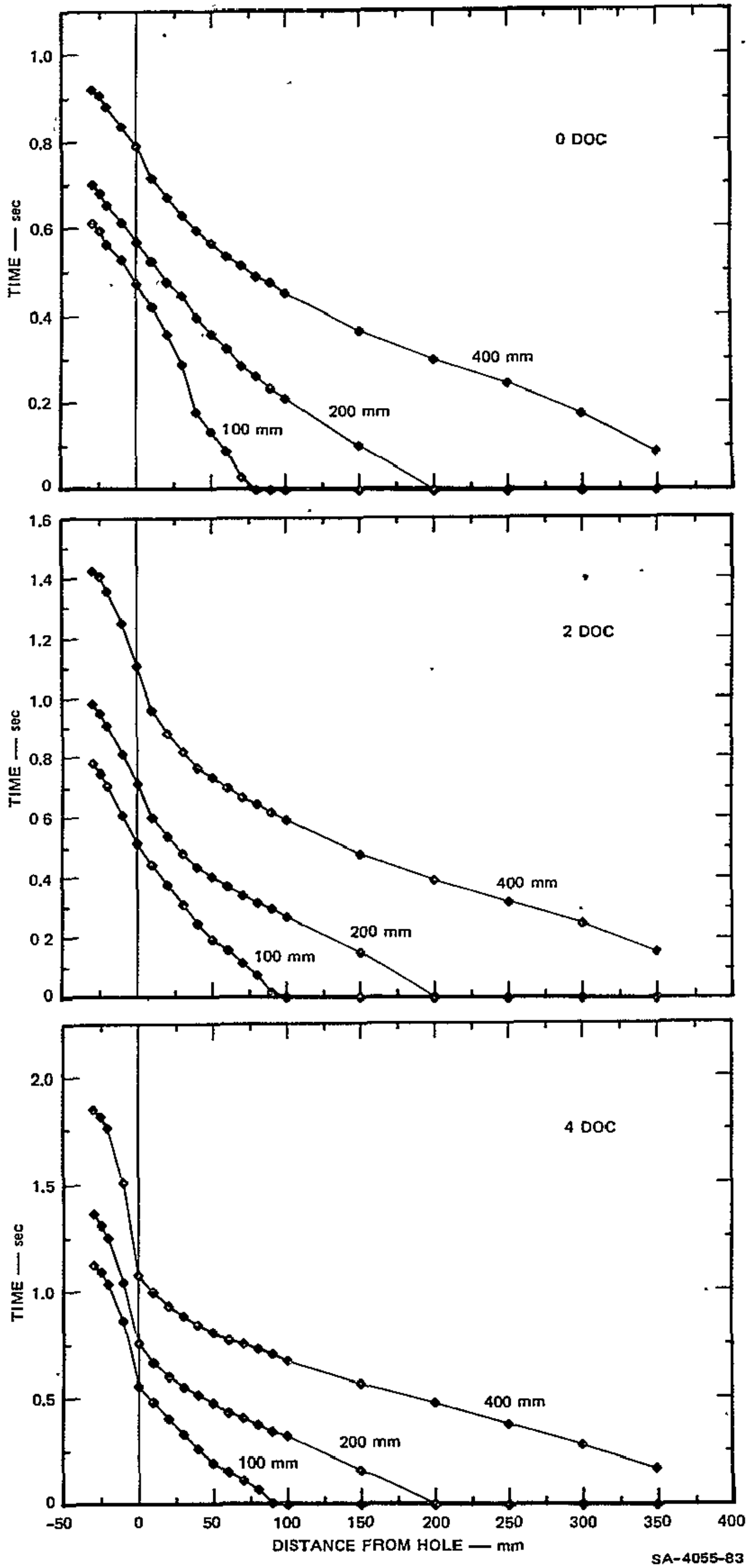


FIGURE 14 MA-11 TRAJECTORIES WITH INCREASING DEGREES OF CONSTRAINT

subjects who served in both the force and no-force conditions. The experiment was balanced for practice effects by starting one subject on the force and the other on the no-force condition and running the two through the design in reverse directions.

The task times shown in Figure 15 are of the same shape as those of the MA-11. Generally the MA-23 is about 30% slower than the MA-11 with force feedback and about 25% slower without force feedback than with it. A statistical treatment of the data must be performed to determine whether these differences are meaningful.

The accumulated trajectories shown in Figure 16 also indicate the general reduction in task time with force feedback. There is a slowing down near the receptacle entrance (between 0 and 10 mm from receptacle) when force feedback is absent. The trajectories of Figure 17 confirm this, the last 10 mm of the 4 DOC insertion taking about twice as long as that part of the insertion without force feedback. The general increase in time without force feedback is apparent throughout the results; gross trajectories as well as fitting movements require more time. With the shortest trajectory (100 mm from the receptacle) gross motion and fitting are intertwined, and it may be impossible to separate these motions (or therbligs) from the data without a model.

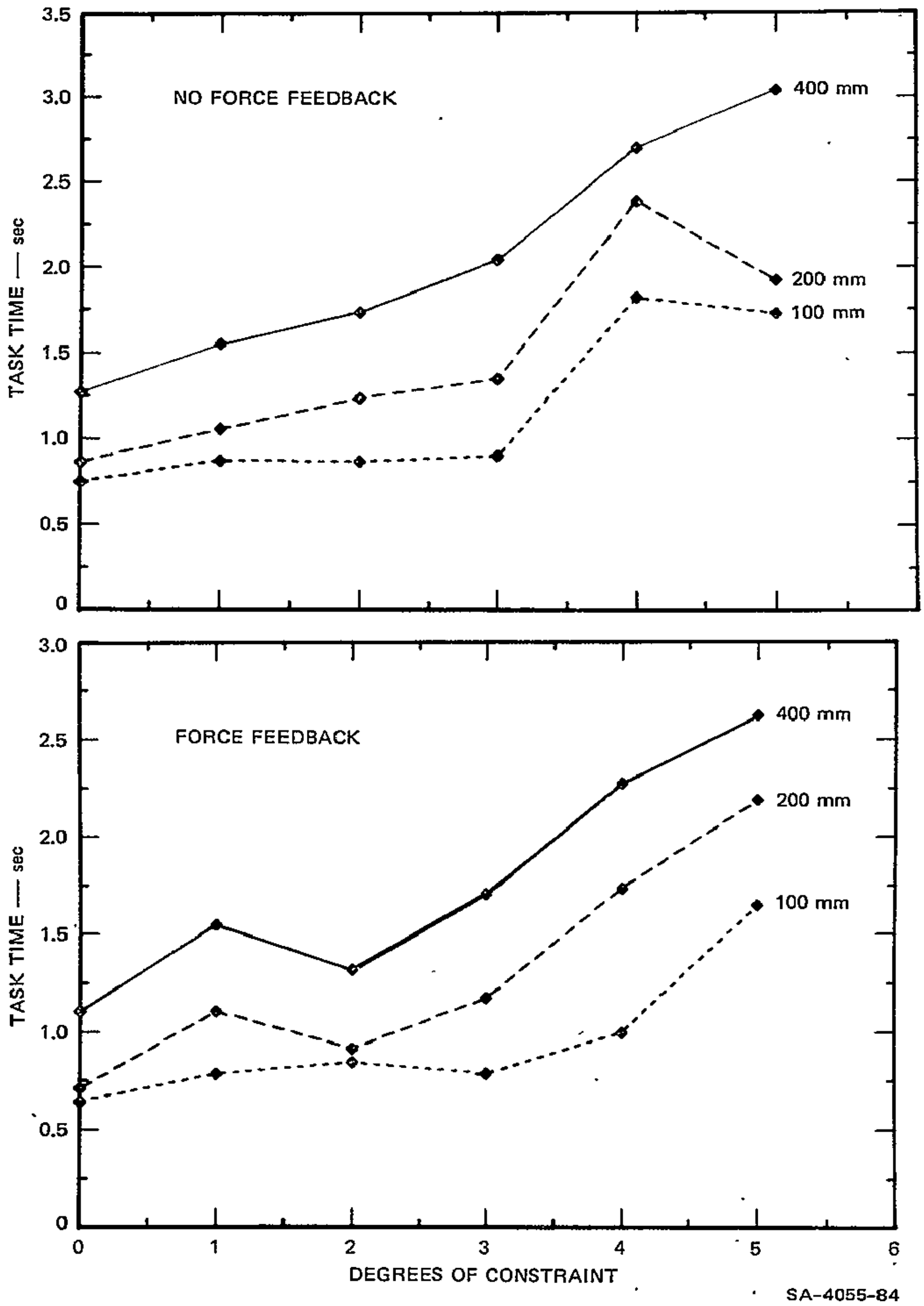


FIGURE 15 COMPARISON OF MA-23 COMPLETION TIMES WITH AND WITHOUT FORCE FEEDBACK

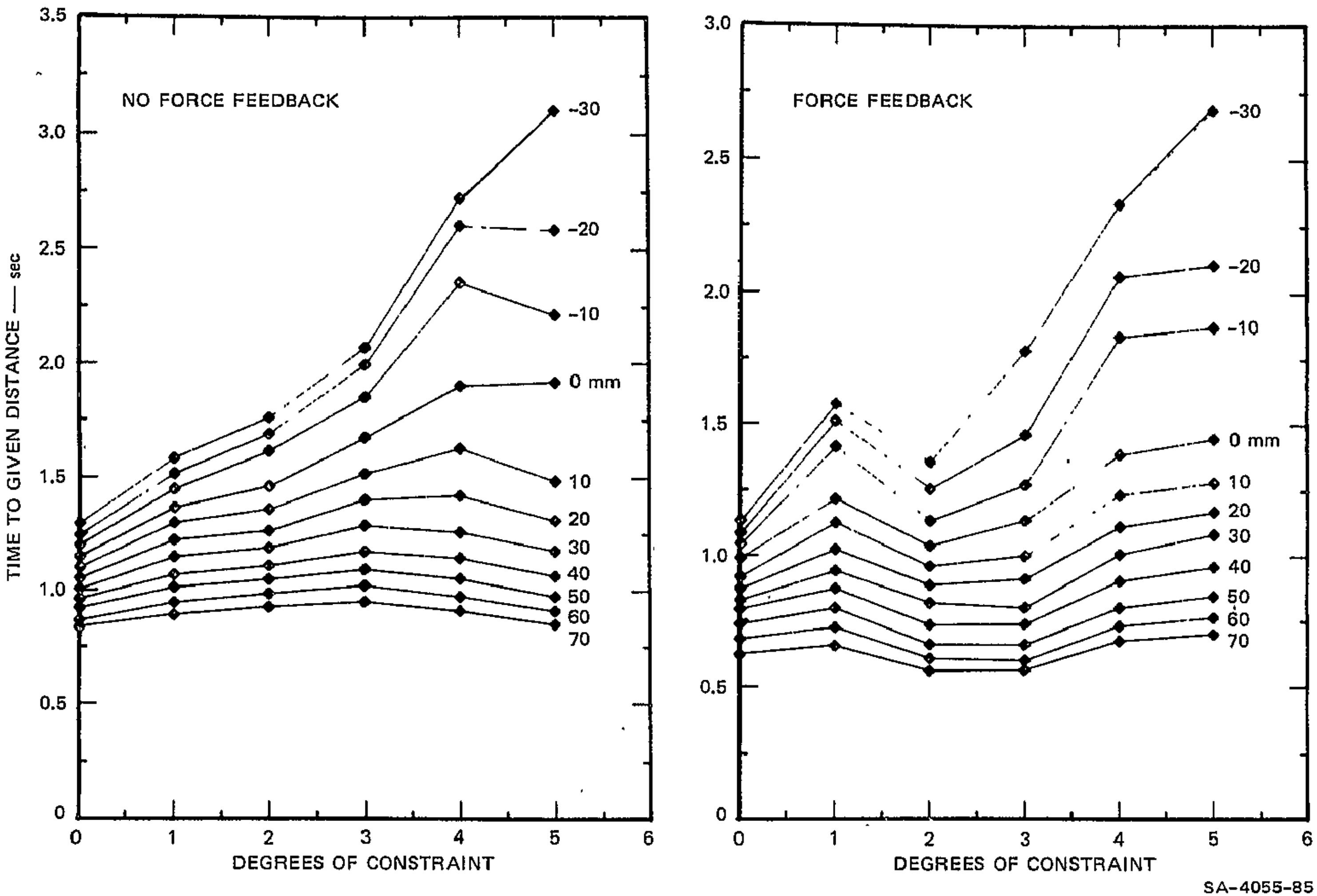


FIGURE 16 MA-23 ACCUMULATED DISTANCES FOR THE 400-mm TRAJECTORIES

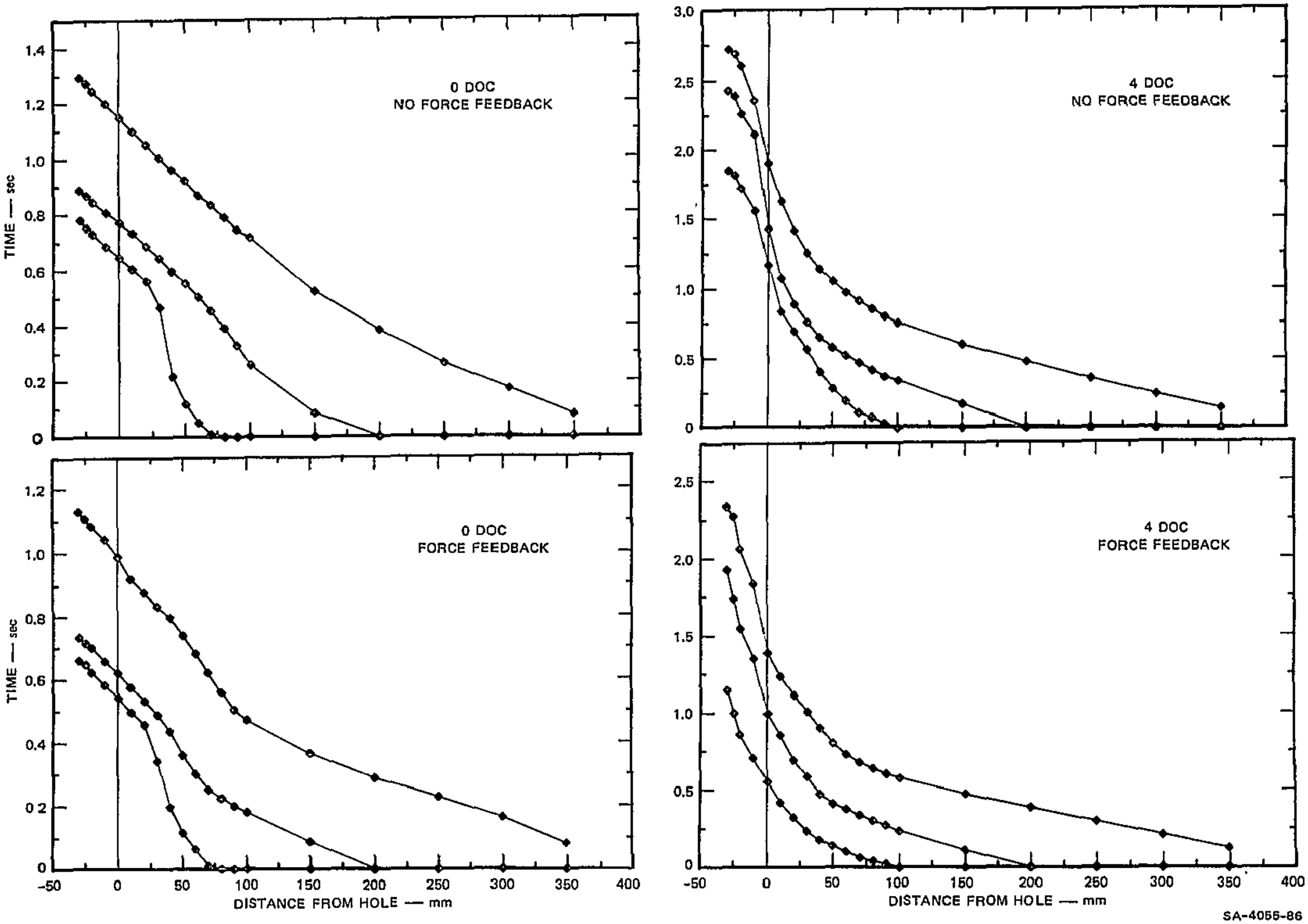


FIGURE 17 COMPARISON OF MA-23 TRAJECTORIES WITH AND WITHOUT FORCE FEEDBACK

IV PEG-IN-HOLE EXPERIMENT

This experiment is similar to the DOC experiment described in Section III and was run at the same time, in the same manner, and with the same test subjects. The object of the task was to insert a set of pegs into a round receptable. The difficulty of the experiment was varied by using pegs of different diameter. The experimental apparatus is basically the same as that used by McGovern.[2] The same pegs were used but a more precise receptacle was built, the previous one being found to be 0.33 mm oversize and 0.2 mm out of round.

A. Apparatus

The apparatus consists of the task board as shown in Figure 3 with a round receptacle and a set of cylindrical pegs. The dimensions of the round receptacle and the pegs are given in Appendix B.

B. Manipulators

The MA-11 and MA-23, described in Section III, were used in this experiment.

C. Experimental Design

The experimental design is basically the same as that of the DOC experiment described in Section III, except that seven pegs of different diameter replace the six different DOC conditions. The design is a 7 X 3 X 8 factorial design similar to that shown in Figure 11. Seven pegs were used (Pegs 2, 4, 6, 8, 10, 12, and 14, which are dimensioned in Appendix B); three distances were used (100-, 200-, and 400-mm trajectories); and 8 repeated runs were made with each condition. The experimental order is the same as that shown in Table 1 with the peg numbers (starting with Peg 2) replacing the ascending degrees of constraint.

D. Procedure

The experimental procedure was the same as that described in Section III.

E. MA-11 Preliminary Results

Basic task times for the peg-in-hole task are shown in Figure 18. These times increase as the difficulty of the task (peg number) increases. The times are longer, particularly with the largest pegs, than those of the DOC task, indicating an increased difficulty. Differences between the three trajectory distances appear to be constant, all three changing in the same increasing manner with peg number. This indicates that the times are accounted for by the sum of two functions; one a function of trajectory length, the other a function of peg number (difficulty).

Since the tolerance of fit of each peg is half that of the preceding peg, the abscissa on Figure 18 is also a measure of task difficulty as defined by Fitts.[4] An interesting feature of the results is their upward curvature: task time is an accelerating function of difficulty, whereas Fitts' law predicts a linear function of difficulty. Statistical analyses to test the linearity of the curves as well as the independence of trajectory length and difficulty (peg number) are planned.

Approach times to different distances to the receptacle were obtained and are shown in Figure 19. These results are similar to those of the DOC experiment previously described (see Figure 13). To within 10 mm of the receptacle, the task time is practically independent of peg size. The insertion time, the time to move from 0 to -25 mm on the graphs, varies greatly with task difficulty. Insertion time is about six times longer with the most difficult peg (Peg 14) than with the smallest peg (Peg 2).

Trajectories for Pegs 2, 8, and 14 are shown in Figure 20. The trajectories show a transition between the smooth insertions with Peg 2 to the two-stage insertion with Peg 14, where the insertion is practically stopped at the entrance to the hole. Similar transitions between smooth and two-stage insertions were observed in the DOC experiment as the task difficulty was increased. The peg-in-hole tasks have a wider range of difficulties, and thus a wider variety of trajectories is observed.

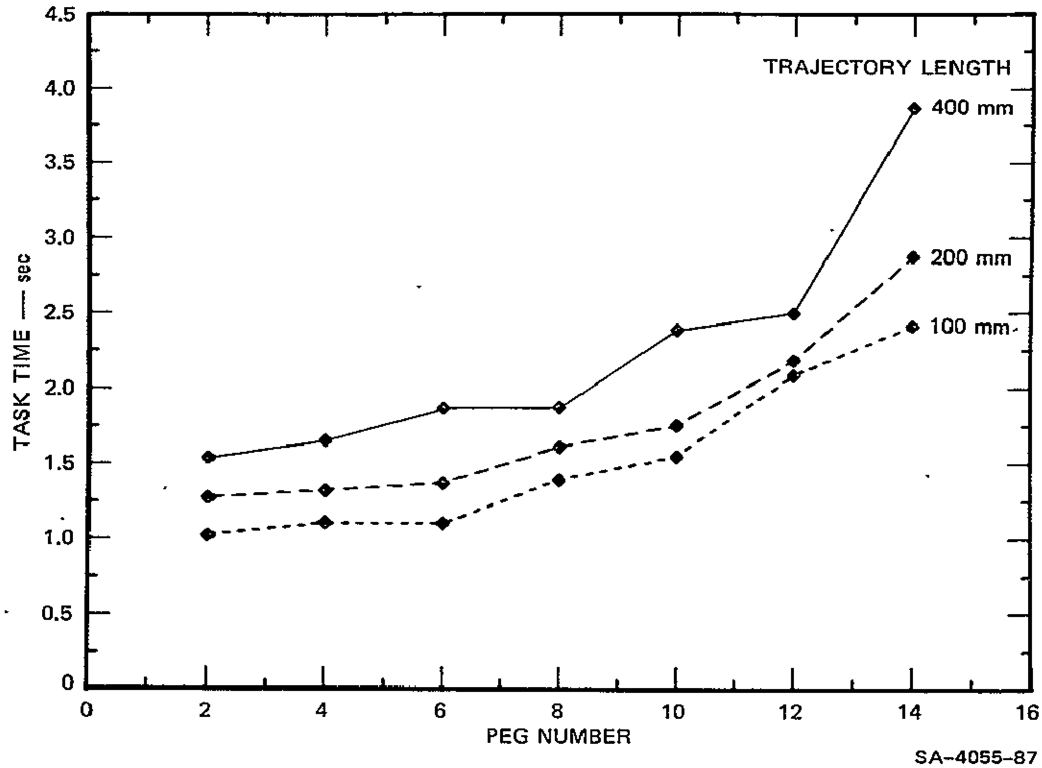


FIGURE 18 MA-11 TASK COMPLETION TIMES

F. Preliminary Comparison of MA-23 With and Without Force Feedback

The results of this comparative experiment are very similar to those of the DOC experiment previously described. The peg results shown in Figures 21, 22, and 23 are similar to the DOC results in Figures 15, 16, and 17, and only the differences will be discussed. The peg results are based on the average data of two subjects who each made eight insertions in each experimental condition.

When force feedback is provided to the operator, the task completion times are reduced 30 to 40% (Figure. 21). There are no distinctive changes as the peg number increases except for the most difficult peg (Peg 14). Here the insertion time is about double when force feedback is removed. These same results are also seen in the more detailed presentation (Figures 22 and 23).

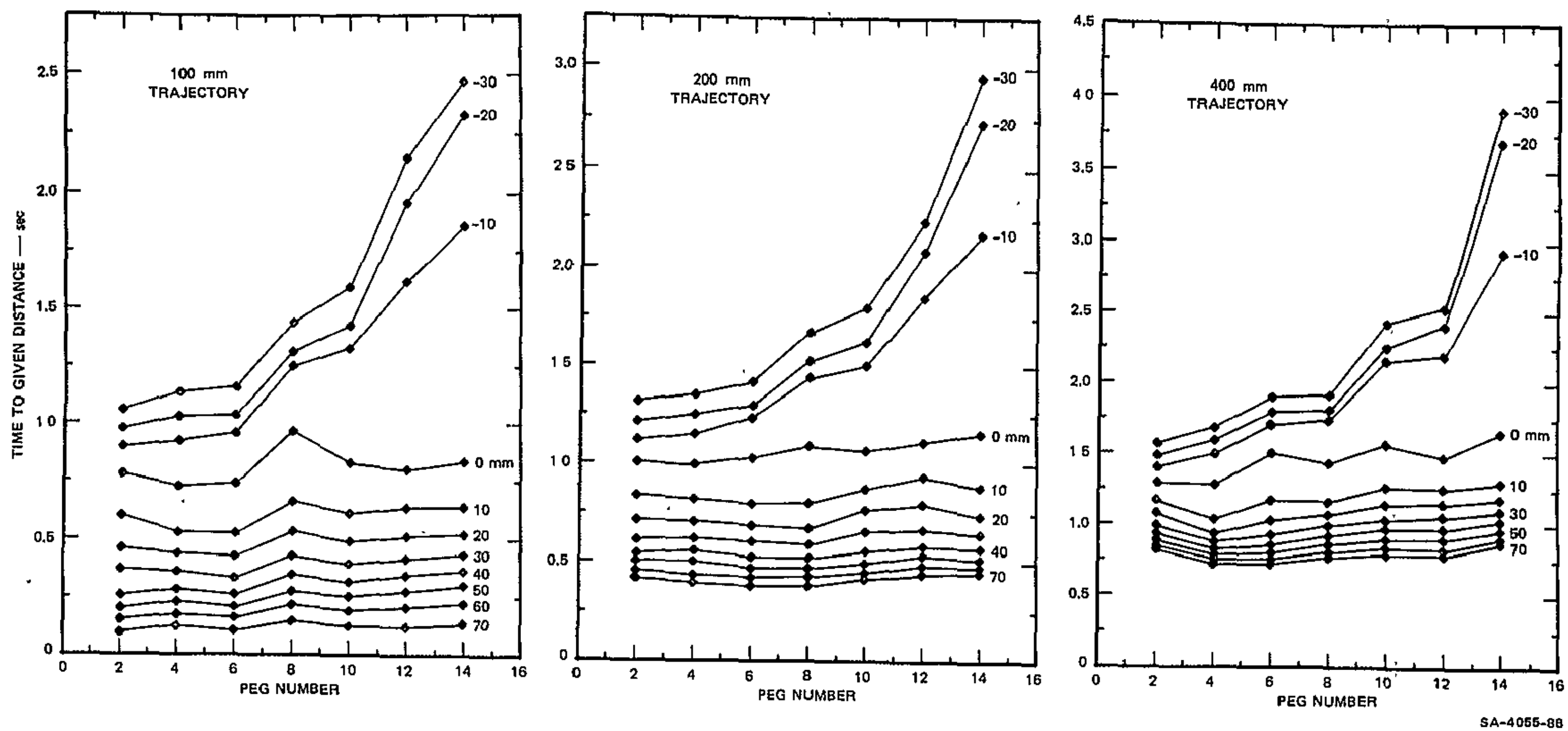


FIGURE 19 MA-11 APPROACH TIMES FOR DIFFERENT DISTANCES TO THE RECEPTACLE

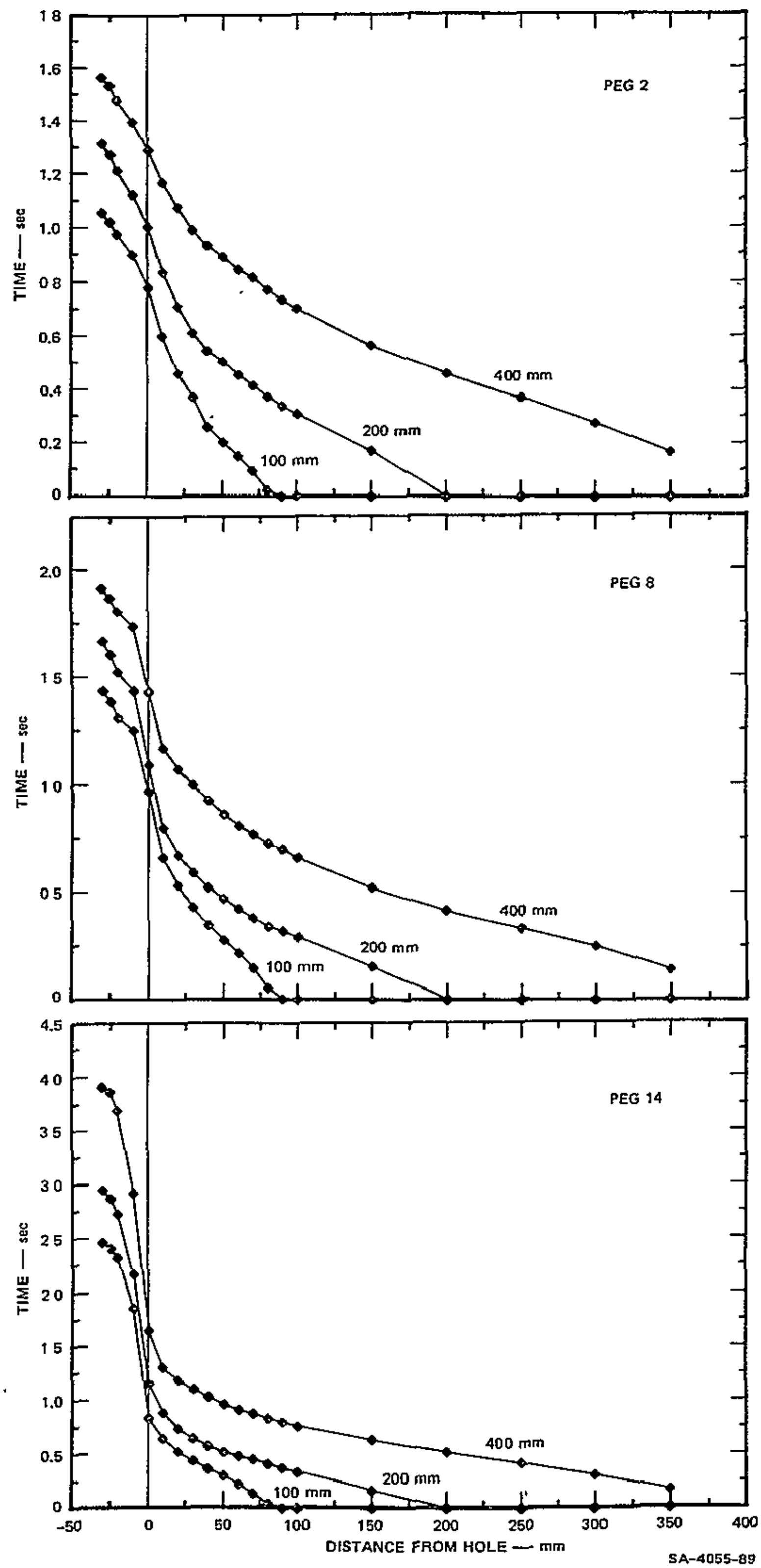


FIGURE 20 MA-11 TRAJECTORIES WITH INCREASINGLY DIFFICULT PEGS

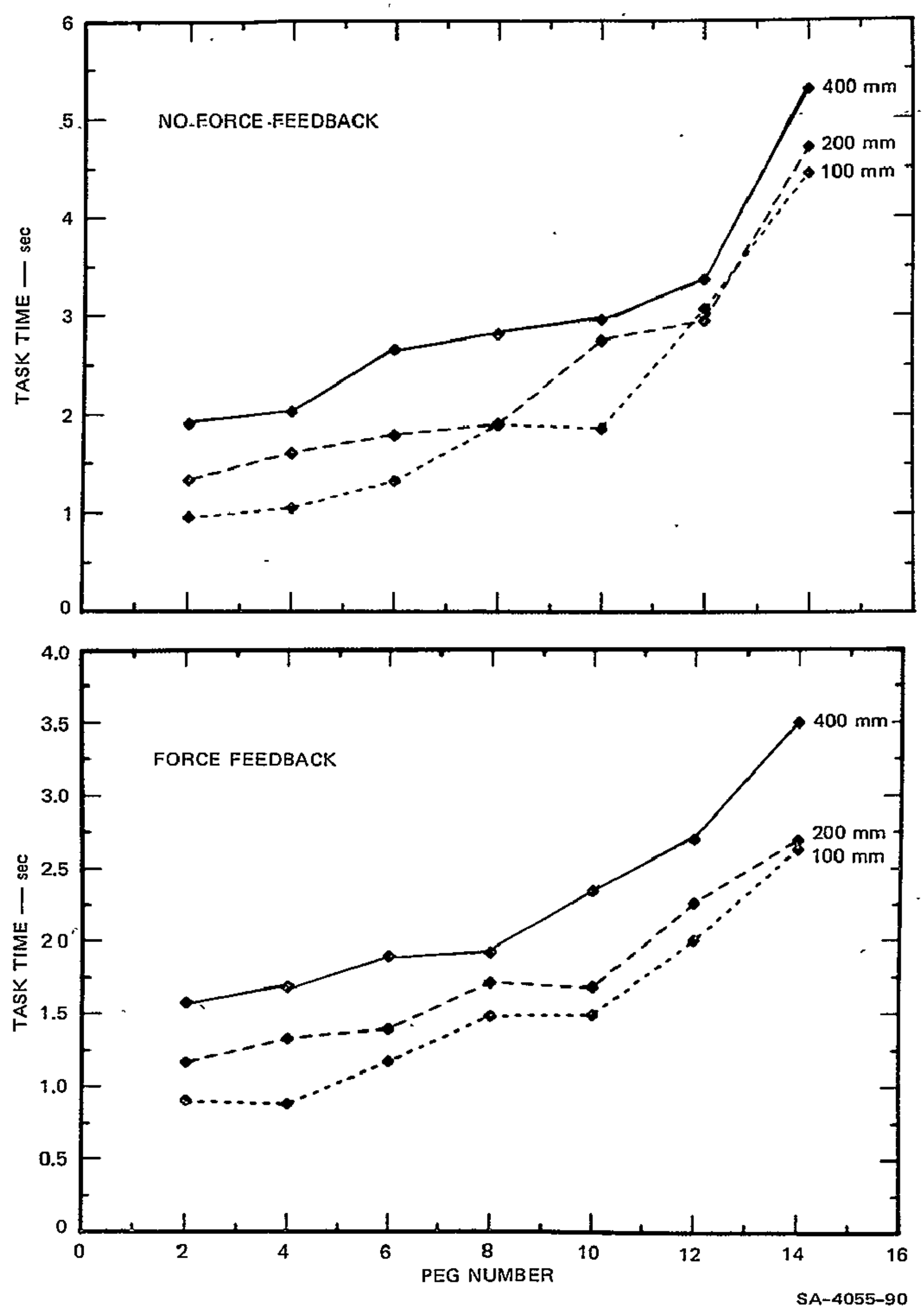


FIGURE 21 COMPARISON OF TASK COMPLETION TIMES WITH AND WITHOUT FORCE FEEDBACK

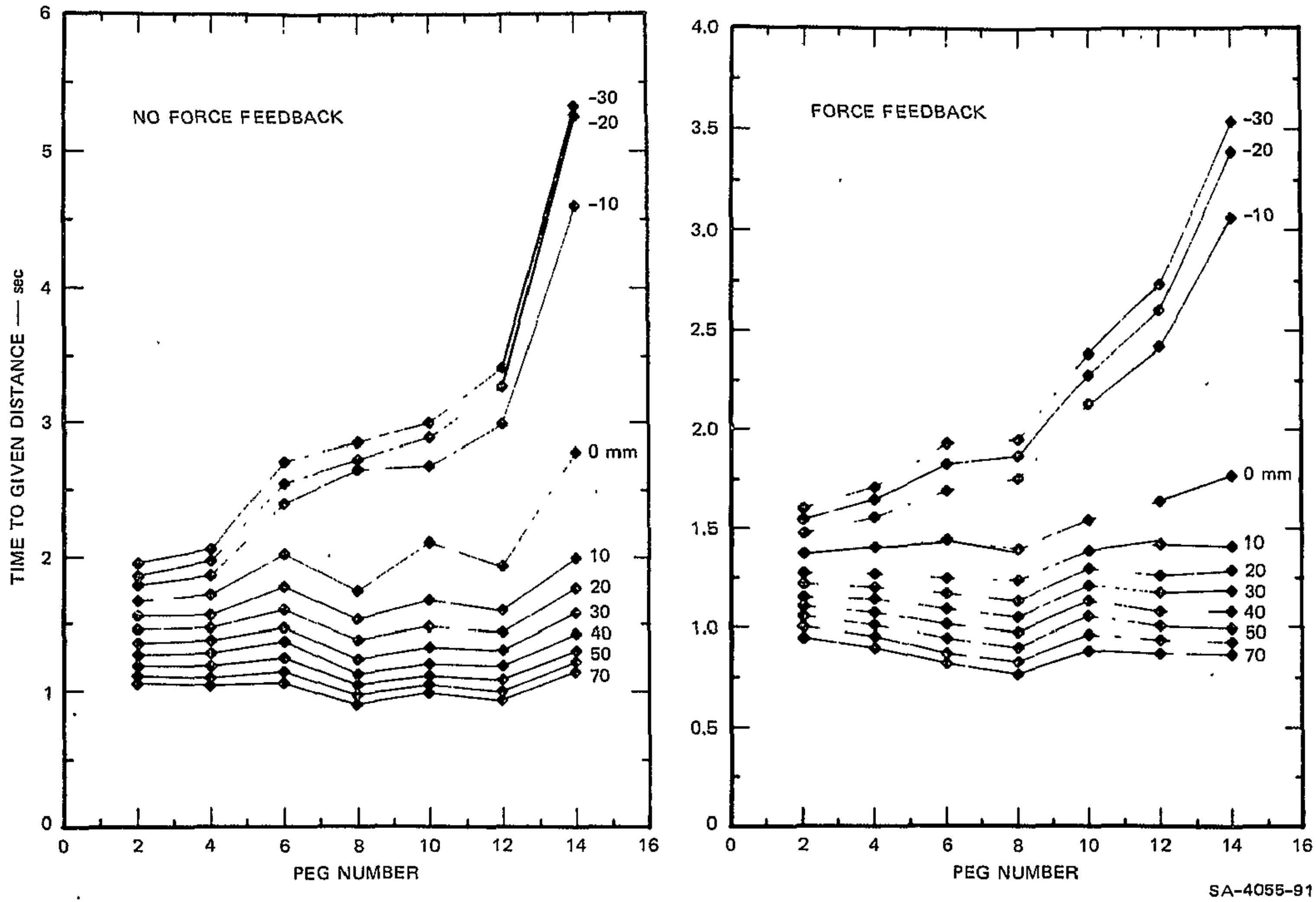


FIGURE 22 MA-23 ACCUMULATED DISTANCES FOR THE 400-mm TRAJECTORIES

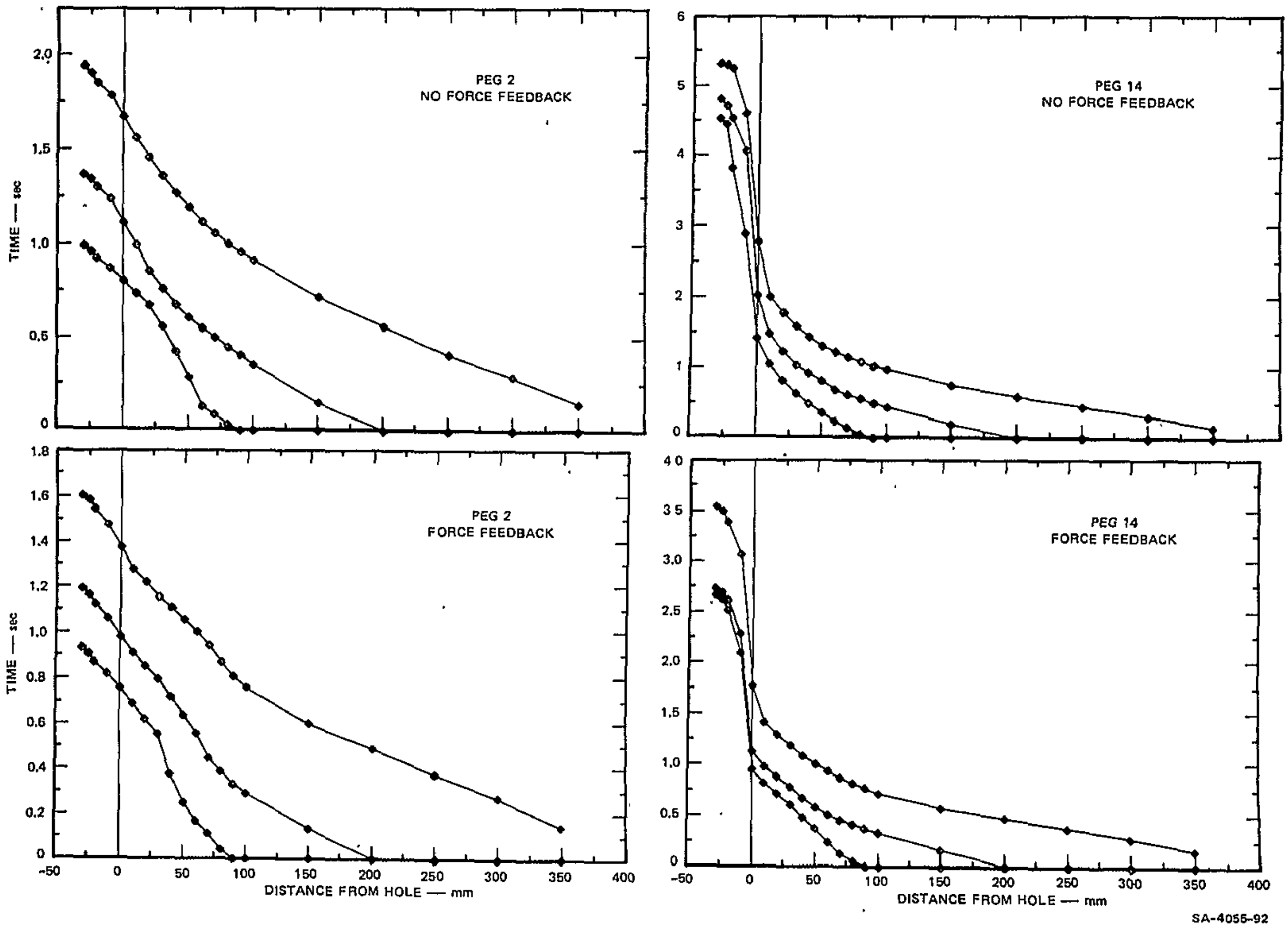


FIGURE 23 COMPARISON OF MA-23 TRAJECTORIES WITH AND WITHOUT FORCE FEEDBACK

V STATISTICAL ANALYSIS OF THE PREVIOUS EXPERIMENTS

The four experiments described in Sections III and IV were given statistical analyses to determine whether differences between manipulators and force-feedback conditions were statistically significant. Analyses of variance were performed on the total task times to obtain the statistics for testing these hypotheses. The results are given below.

A. MA-11 Manipulator--6-DOC Task

Task time is a strong function of the degrees of constraint [$F(5,252) = 57.10$, $p < 0.001$], and there is insufficient evidence to show that it is not a linear function [$F(4,252) = 0.42$, $p > 0.05$]. Similarly, the task time is a strong function of trajectory length [$F(2,252) = 93.08$, $p < 0.001$] and there is insufficient evidence to show that it is not a linear function [$F(1,252) = 0.01$, $p > 0.05$]. Also, there is insufficient evidence to show an interaction (or dependence) between these two linear functions [$F(10,252) = 1.62$, $p > 0.05$]. With the results of these five tests, we may assume a linear model of the form

$$\text{Task time} = K_1(\text{DOC}) + K_2(\text{trajectory length}) \quad , \qquad (1)$$

where K_1 and K_2 are linear functions. Thus, the total task time may be broken down into the sum of two linear, independent functions.

B. MA-11 Manipulator--Peg-in-Hole Task

Task time is a strong function of the peg number [$F(1,294) = 56.49$, $p < 0.001$] and is nonlinear [$F(4,294) = 12.4$, $p < 0.001$]. As with the DOC task, task time is a strong function of the trajectory length [$F(2,294) = 43.80$, $p < 0.001$] but there is insufficient evidence to show that it is nonlinear [$F(1,294) = 0.05$, $p > 0.05$]. The interaction between peg and trajectory length [$F(12,294) = 1.69$, $p > 0.05$] is not statistically significant, again suggesting independence between these two parameters. With this information, we can assume the following model for this task:

$$\text{Task time} = f_1(\text{peg}) + K_2(\text{trajectory length}) \quad , \qquad (2)$$

where f_1 is an accelerating function of the peg number and K_2 is the same linear function we had with the 6-DOC task [Equation (1)].

C. MA-23 Manipulator--6-DOC Task With and Without Force Feedback

Task-completion times with force feedback are significantly shorter than without force feedback [$F(1,504) = 68.91$, $p < 0.001$]. Task-completion times are also strong functions of the degrees of constraint and trajectory length, both being statistically significant ($p < 0.001$). Task-completion time is not a linear function of the DOC as it was with the MA-11, since the nonlinear term [$F(4,504) = 26.62$, $p < 0.001$] is statistically significant. The nonlinear term for trajectory length, [$F(1,504) = 3.26$, $p > 0.05$] is not statistically significant, again suggesting a linear function of trajectory length. Of the three interactions between these three variables, force by DOC is significant ($p < 0.001$), force by trajectory length is not significant ($p > 0.05$), and DOC by trajectory length is ($p < 0.001$).

Because of these interactions, the MA-23 results are more difficult to interpret than those of the MA-11.

D. MA-23 Manipulator--Peg-in-Hole Task With and Without Force Feedback

Task-completion times with force feedback are significantly shorter than without it [$F(1,588) = 129$, $p < 0.001$]. Task-completion times are also strong functions of the peg size and the trajectory length, both being statistically significant at the 0.001 level. Task-completion times are nonlinear functions of the peg number, as with the MA-11, because the nonlinear term is statistically significant at the 0.001 level [$F(5,588) = 19.16$, $p < 0.001$]. The nonlinear term in the trajectory length [$F(1,588) = 0.19$, $p > 0.05$] is not significant, indicating that, again, the time is a linear function of trajectory length. Of the three interactions, force feedback and peg number interact significantly ($p < 0.001$), whereas force feedback and trajectory length do not ($p > 0.05$) and peg number and trajectory length do not ($p > 0.05$). These results indicate that there are two models for MA-23 performance in this task. With force feedback we have

$$\text{Task time} = f_f(\text{peg}) + K_2(\text{trajectory length}) \tag{3}$$

and without force feedback we have

$$\text{Task time} = f_{\bar{f}}(\text{peg}) + K_2(\text{trajectory length}) \quad , \tag{4}$$

where the two curving functions of peg size, f_f and $f_{\bar{f}}$, are different, and the linear functions of trajectory length, K_2, are identical.

E. Summary

One of the interesting results of these analyses is that in all four cases analyzed above, task time is directly proportional to trajectory length. Thus the distance moved appears to be a basic measure of manipulator performance, independent of manipulator, force feedback, and task. This basic result is explored further and modeled in the paper reprinted in Appendix A.

VI VIEWING EXPERIMENTS WITH THE AMES ARM

A series of manipulation experiments were run using the Ames Arm to perform the peg-in-hole task described in Section IV. The object of the evaluations is to distinguish between the abilities to perform the task (which ranged from low- to high-precision fits) as a function of the viewing condition. The following different viewing conditions were provided, all with the viewing point 2 m in front of the task:

- Direct viewing, with the subject sitting in front of the task area (see Figure 24)
- Single-camera TV viewing (situation shown in Figure 25)
- Stereo TV viewing with split screen (situation shown in Figure 25)
- Head-aimed stereo TV viewing (shown in Figure 26).

The experiment was run with two subjects and all four of the viewing conditions above. The experiment was also run using the unaided human hand for comparison with Fitts'[5] basic study. The data have not yet been analyzed or plotted. Stereo and mono TV presentations were made with a closed-circuit TV system utilizing a split-screen technique: half of the screen was imaged on each eye. Images used in the experiments (photographed off the TV screen) are shown in Figure 27.

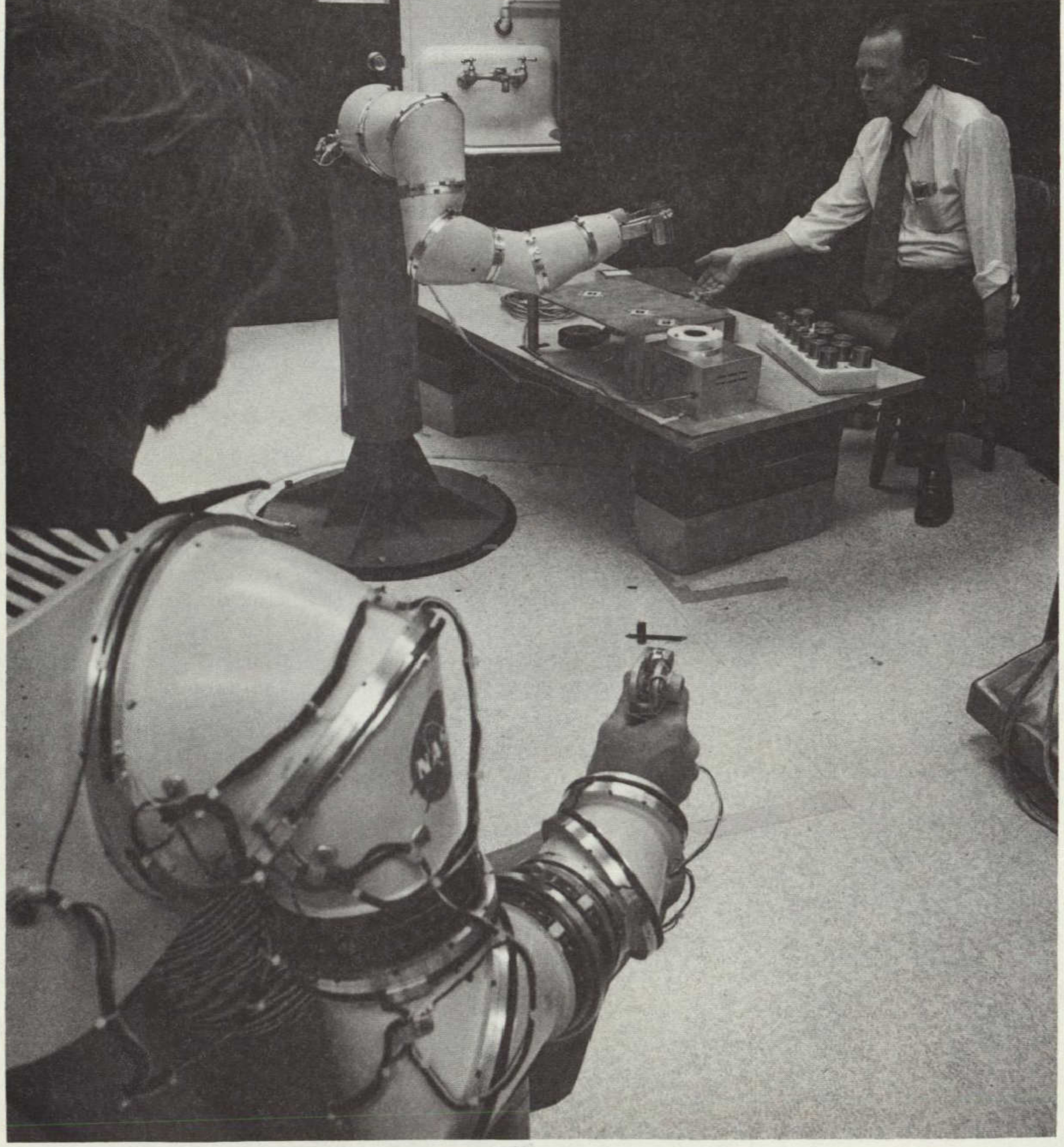
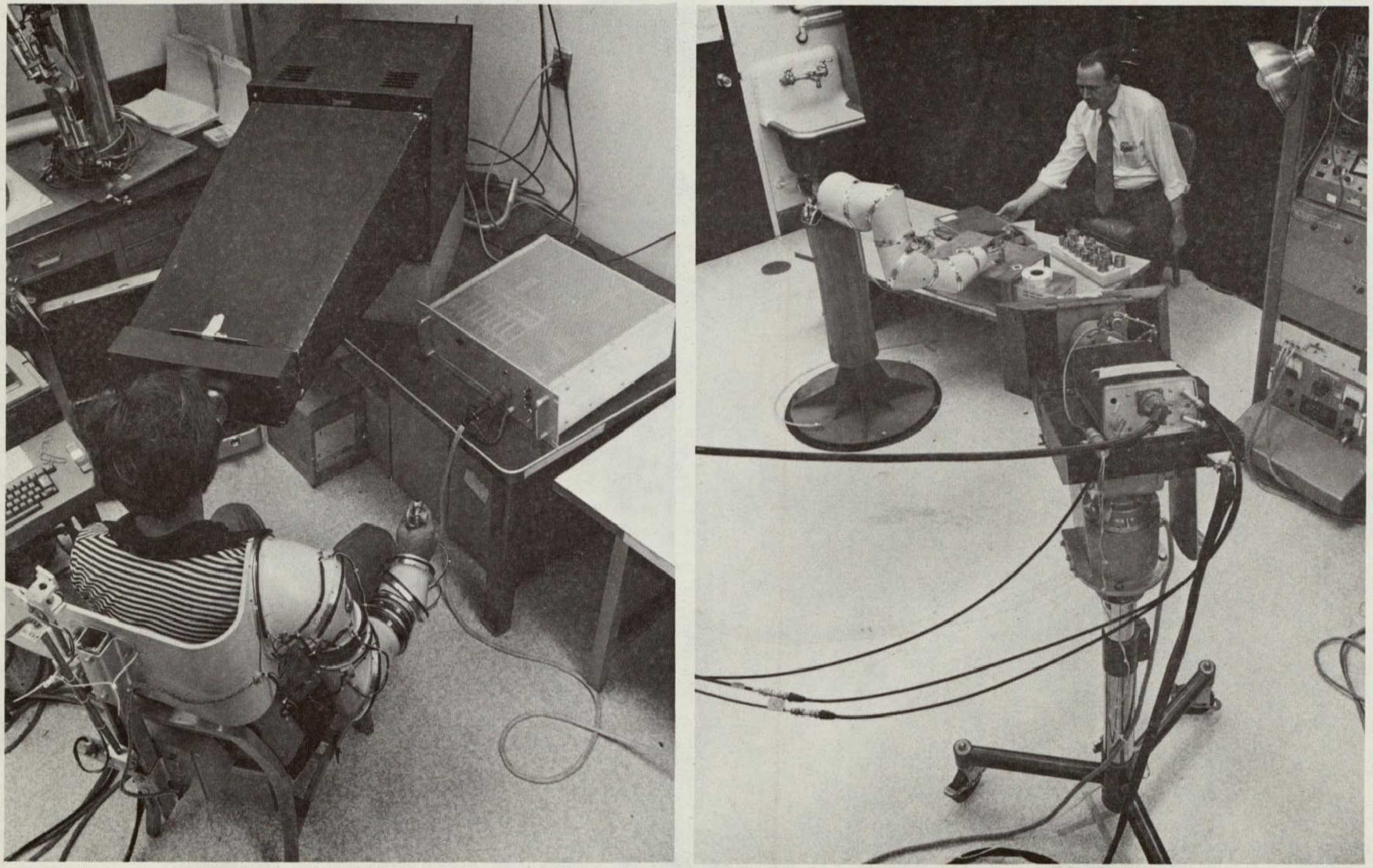


FIGURE 24 DIRECT-VIEWING CONDITION



(a) SUBJECT VIEWING TV

(b) EXPERIMENTER WITH TV CAMERA

FIGURE 25 MONO AND STEREO VIEWING CONDITION

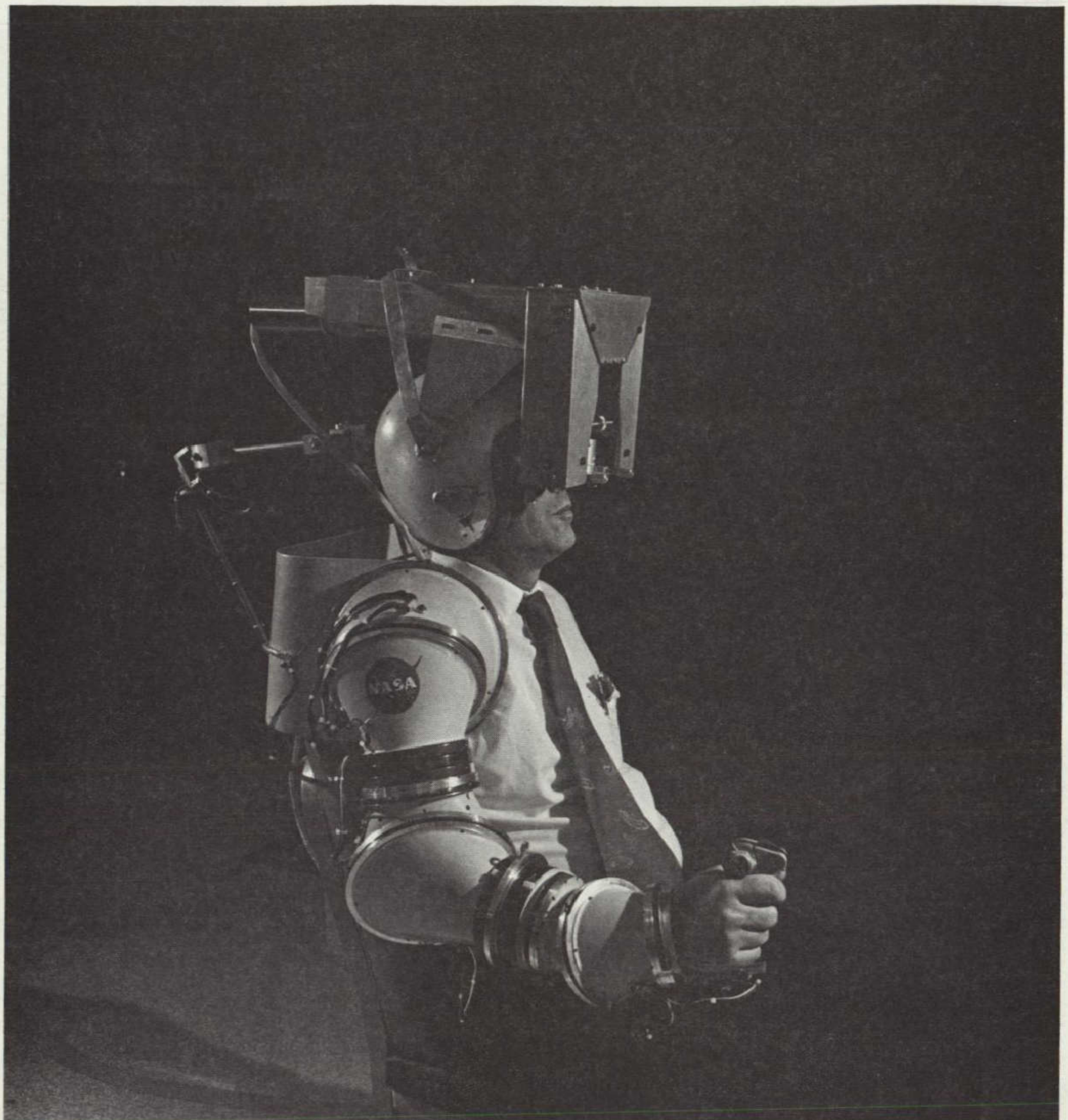
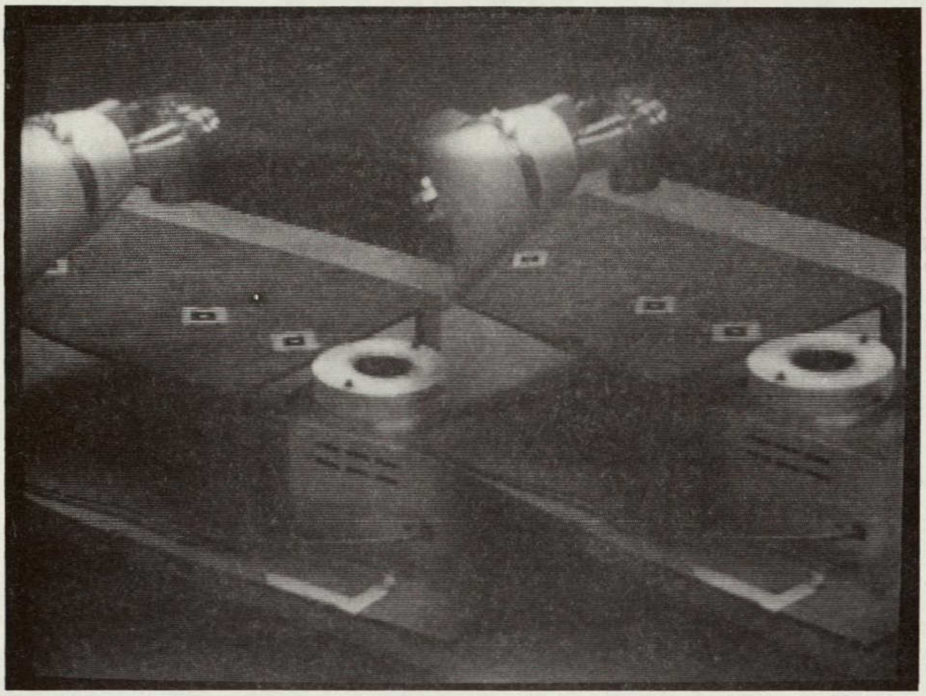
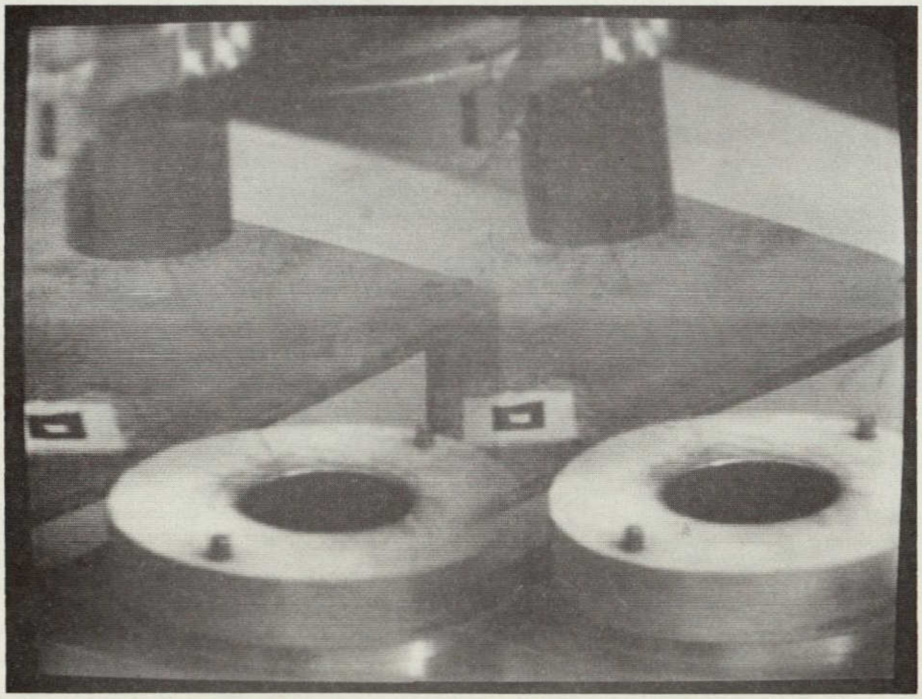


FIGURE 26 SUBJECT WITH HEAD-AIMED STEREO SYSTEM



(a) ENTIRE-TASK USED IN STEREO AND MONO EXPERIMENTS



(b) CLOSE-UP VIEW POSSIBLE WITH HEAD-AIMED SYSTEM

FIGURE 27 SPLIT-SCREEN PRESENTATIONS

Based on these criteria, the controller shown in Figure 28 has been designed. The design includes detailed parts drawings, cableing diagrams, and torque motor specifications. The unique features of the design are the gimballed hand grip and the telescoping joint. The kinematic design of Figure 29--designating the joints--shows the unit's simplicity. The first four joints (q_1, q_2, q_3, and q_4) are cable-controlled from four actuators at the end of the telescopic joint. The cables are all conveyed through a counterbalanced take-up mechanism in the telescopic joint, enabling the hand grip to move while the actuators remain stationary. Thus, the actuators also serve as weights for counterbalancing the hand grip. Detailed specifications on the controller are given in Table 2.

Because of the intersecting axes, the mathematics for transforming back and forth between the grip and base reference frames of the controller is straightforward.

If the individual joint motions in homogeneous coordinates are represented by

$$R_x(q_i) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C_i & -S_i & 0 \\ 0 & S_i & C_i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} , \tag{5}$$

$$R_y(q_i) = \begin{bmatrix} C_i & 0 & S_i & 0 \\ 0 & 1 & 0 & 0 \\ -S_i & 0 & C_i & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} , \tag{6}$$

$$R_z(q_i) = \begin{bmatrix} C_i & -S_i & 0 & 0 \\ S_i & C_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} , \tag{7}$$

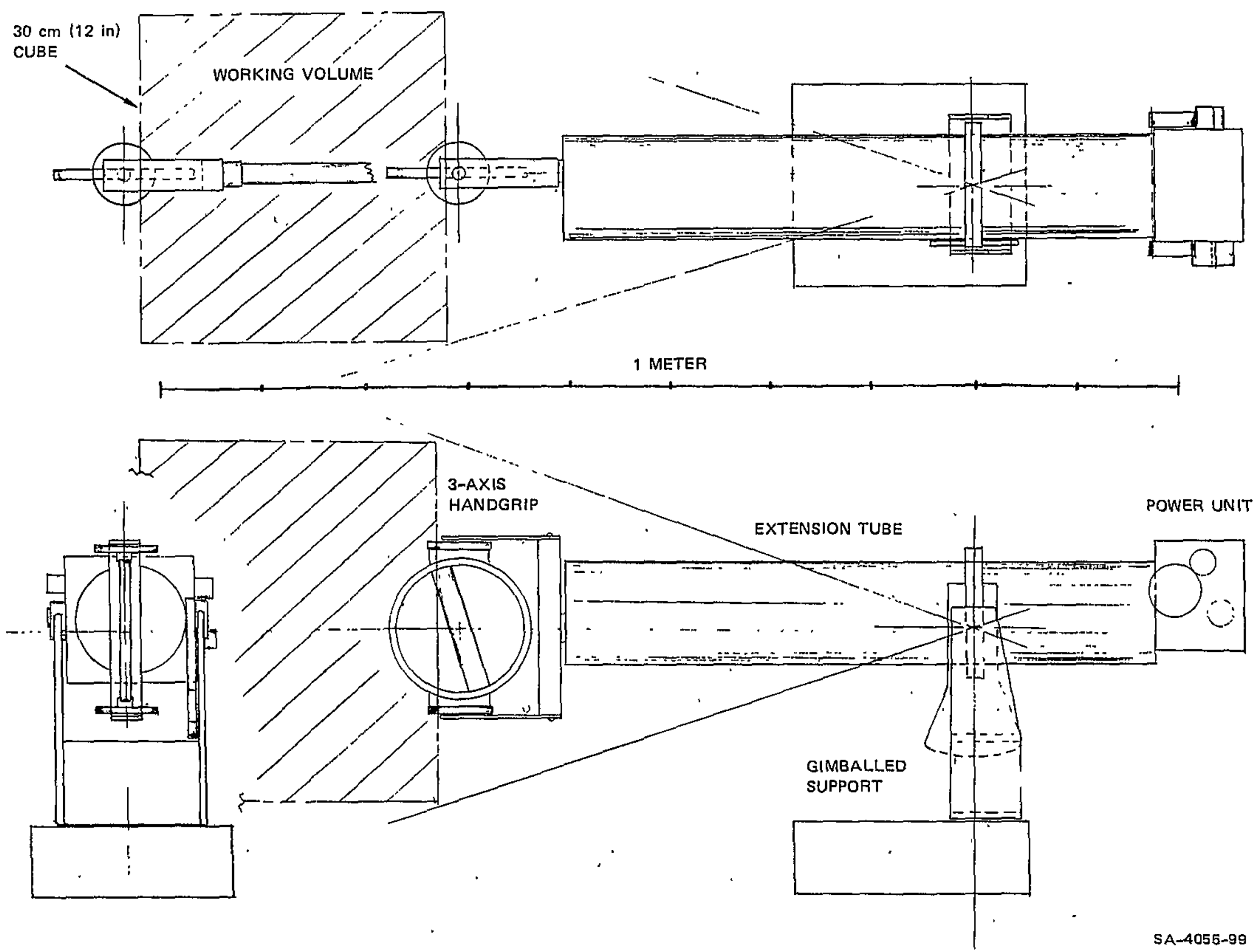


FIGURE 28 SIX-AXIS, FORCE-REFLECTING CONTROLLER

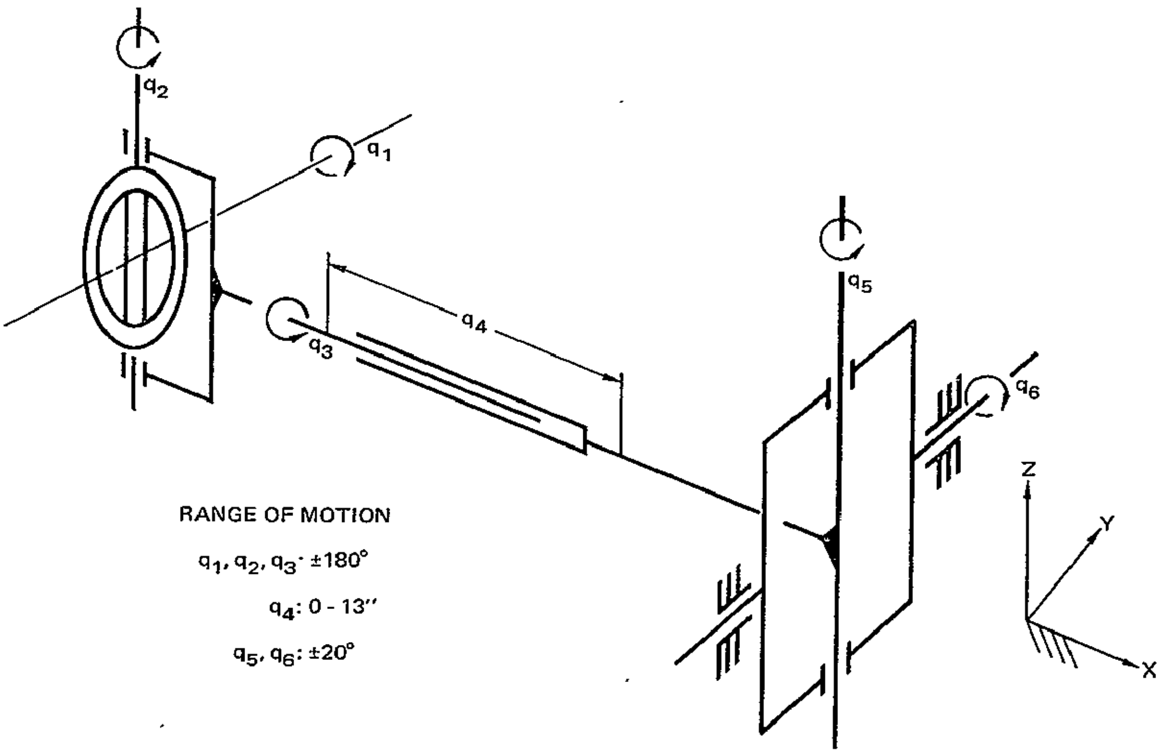


FIGURE 29 CONTROLLER KINEMATICS

Table 2

CONTROLLER SPECIFICATIONS

(a) Three-Axis Hand Grip

Joint	Torque, T_{max} (kg-cm)	Friction* (kg-cm)	Effective Inertia† (kg-cm^2)	Acceleration‡ (krad/sec^2)	Power at T_{max} (watts)	Motor
q_1	5	0.12	0.76	8.6	62	Magtech (40 oz. in) (NASA spec.)
q_2	5	0.12	0.76	8.6	62	Magtech (40 oz. in) (NASA spec.)
q_3	5	0.12	0.76	7.3	62	Magtech (40 oz. in) (NASA spec.)

(b) Extension Tube and Gimballed Support

Joint	Force, F_{max}§ (kg)	Friction* (kg)	Effective Mass† (kg)	Acceleration‡ (g)	Power at F_{max} (watts)	Motor
q_4	1	0.095	0.94	1.25	24	Magtech (170 oz. in) (NASA spec.)
q_5	1-1.65	0.027-0.045	0.49-0.93	2-1.7	67	Magtech (170) 2375-190
q_6	1-1.65	0.027-0.045	0.49-0.93	2-1.7	67	Magtech (170) 2375-190

*Neglects cable bending losses.

†At grip, including drive train and structure.

‡Maximum theoretical.

§Left figure for q_4 extended, right for q_4 retracted.

and

$$T = \begin{bmatrix} 0 & 0 & 0 & T_x \\ 0 & 0 & 0 & T_y \\ 0 & 0 & 0 & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad , \tag{8}$$

where

$$C_i = \cos(q_i) \tag{9}$$

and

$$S_i = \sin(q_i) \quad , \tag{10}$$

then the transform from the grip frame of reference to the fixed frame of reference is

$$\Phi = R_y(q_6) \cdot R_z(q_5) \cdot T(q_4) \cdot R_x(q_3) \cdot R_z(q_2) \cdot R_y(q_1) \quad . \tag{11}$$

In the matrix below, the letters a through i are the direction cosines relating grip orientation to the fixed frame, and x, y, and z are the displacements of the origin of the grip relative to fixed-frame origin:

$$\Phi = \begin{bmatrix} a & b & c & x \\ d & e & f & y \\ g & h & i & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad . \tag{12}$$

VIII GRAPHICS DISPLAY SYSTEM

A. Basic Description of the Display Monitor

This section describes the development of a software display monitor for the GT-40 Graphics Display System. Upon completion of the analog-to-digital interface, this monitor will permit the performance of six-degree-of constraint step-tracking tasks. Rate and position controllers of various designs can be used to drive a perspective (and potentially stereoscopic) CRT display. Static and moving objects can be drawn with a minimum of overhead computation. The display monitor is designed to become an integral part of a supervisory control system for manipulator control, as shown in Figure 30.

The monitor's prime function is to permit a human operator to quickly review, through position, velocity, force, tactile and other sensors, a variety of visual data presentations concerning a manipulator's performance. The GT-40 with range-sensor display is shown in Figure 31.

By using a rate controller (MIT controller)[5] or a position controller (force-reflecting controller, previously described), the operator may point to and otherwise interact with a three-dimensional scene--that is, the operator may observe and intervene in an automatic process as well as assume direct control of manipulators and other positioning devices.

The goal was to develop for the GT-40 Graphics Display a resident monitor with the following capabilities:

- Constant communication with a host computer (or computers).
- Quick down-line loading of display modules from the KL-10 computer.
- Performance of fast coordinate transformations and perspective display of objects.
- Digital and analogic, text, and perspective displays of various quantities.
- Simple keyboard commands to permit rapid display changes.

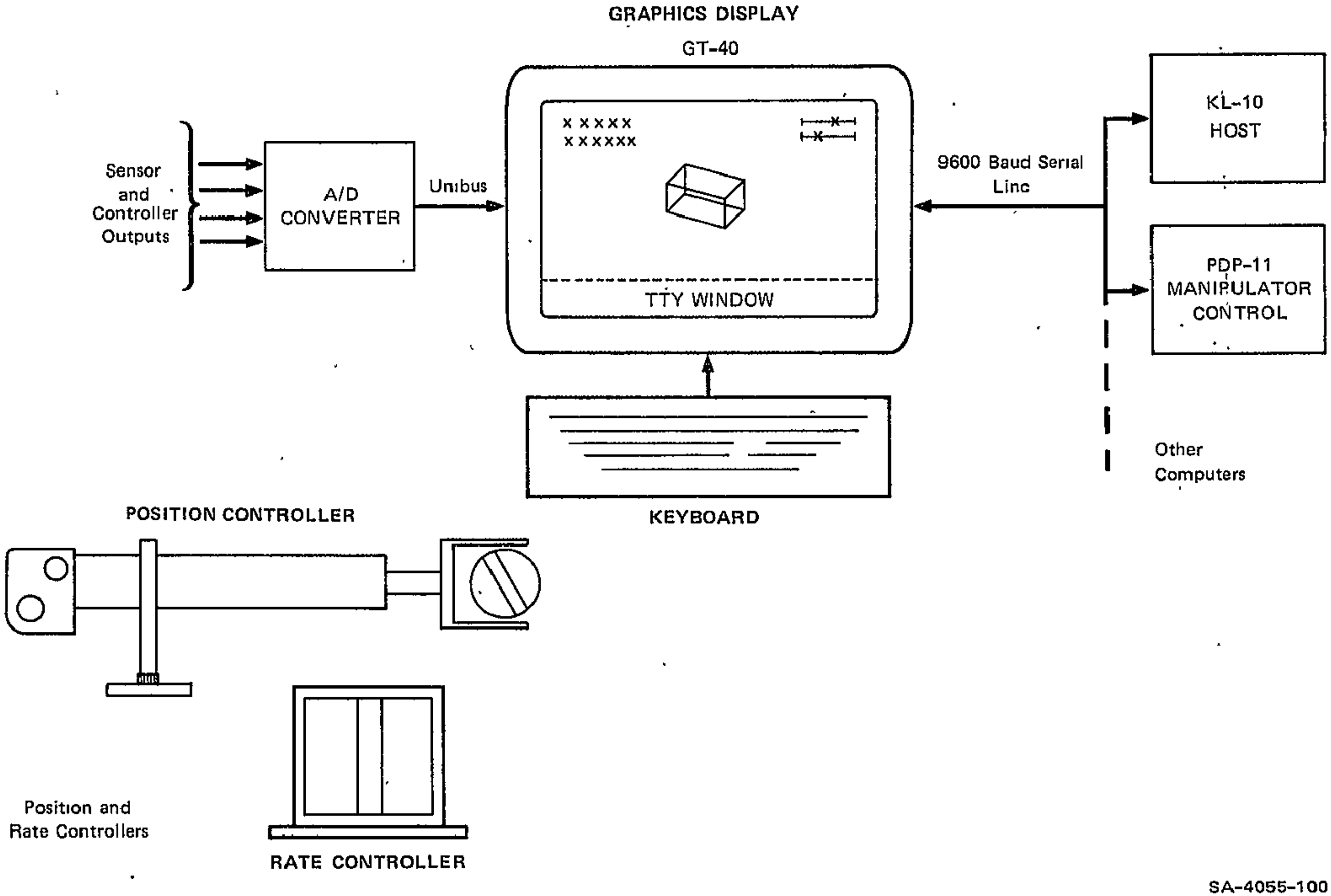


FIGURE 30 DISPLAY MONITOR FOR A SUPERVISORY SYSTEM

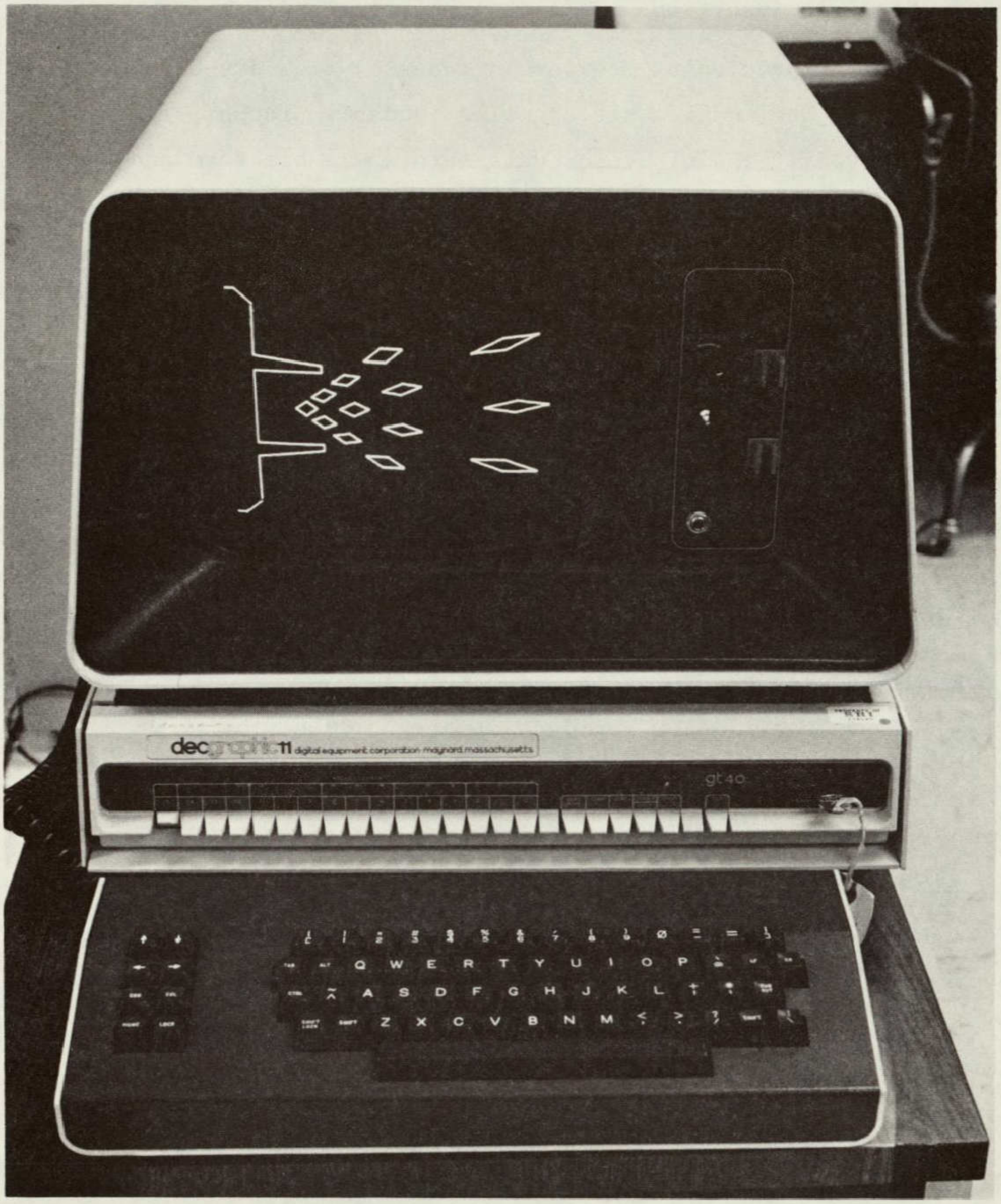


FIGURE 31 DISPLAY CONSOLE SHOWING RANGE-SENSOR OUTPUTS

- A structure permitting eventual/future display modules to be written in a higher-level language and the addition of these new subroutines to the monitor's repertoire.
- Flexible insertion and deletion of display elements.

The resulting display monitor is centered around the concept of display modules. The modules are downline loadable program segments, which control the conversion of sensor data into a useable form and provide display of textual information. Frequently used display modules can be loaded as part of the resident display monitor, thus permitting quicker access to them. The structure of the display monitor is shown in Figure 32.

The monitor's CRT display includes a "teletype window" at the bottom of the screen that permits simultaneous interaction between the monitor and the host computer(s). Thus, display modules may be edited, recompiled, and reloaded even as you watch them in operation. Other types of communication concerning manipulator performance may occur. The host computer(s) may send messages to the operator in three ways:

- Messages typed to the teletype window
- Remote starting of resident display modules.
- Downline loading and starting of display modules.

The operator may talk to the host in three ways:

- Text input from the keyboard
- Automatic text typeout via commands typed at the keyboard
- Automatic text typeout initiated by a display module.

The communications interface is fast enough (1 character/msec) to enable the host computer to specify the position and orientation of a moving object at 50 Hz. Such dedicated use of the serial communications line is probably not advisable and such data is best transmitted via the unibus. It does, however, seem quite reasonable for the host to place static objects in the scene with a message length of 30 characters.

B. Use of the Display Monitor

Several modules have been written to illustrate a variety of display techniques possible with the monitor. The modules can be installed with commands that are explained with a help command (See Figure 33).

The command ";4" (without quotes) currently loads and starts a demonstration program that exercises most of the system subroutines. The program positions a cube on the screen as a function of six values read by the analog-to-digital converter. After scaling and offsetting, the six parameters are used to position the cube via the object transformation previously given for the grip of the force-reflecting controller. A rate mode is also available so that the cube may be caused to move the various linear and angular rates (See Figure 34).

The routine computes the cube position at about 40 Hz. This rate could be increased by precomputing the elements of several intermediate transformations rather than by multiplying six rather sparce matrices. The homogeneous transform representations are used throughout the system. The demonstration program uses screw transforms to effect the object transformations. This is simply a rotation about, and a translation along, a specified axis and easily lends itself to homogeneous representation. It provides an unambiguous specification of relative positions and orientations.

A second target or marker cube is displayed at an arbitrary static position. This location may be changed by the introduction of the address of a new transform to the routine. Thus, in a positioning experiment, new target locations can be installed simply. Alternatively, the target location may be equated to the current grip location, thus permitting the operator to leave a marker in six-dimensional space and move it at will. The display of obstacles and points of interest is a simple extension of these processes (See Figure 35).

C. Display Mathematics

The world coordinates of all displayed objects are generated as a result of the display process and may be used for testing (i.e., collision,

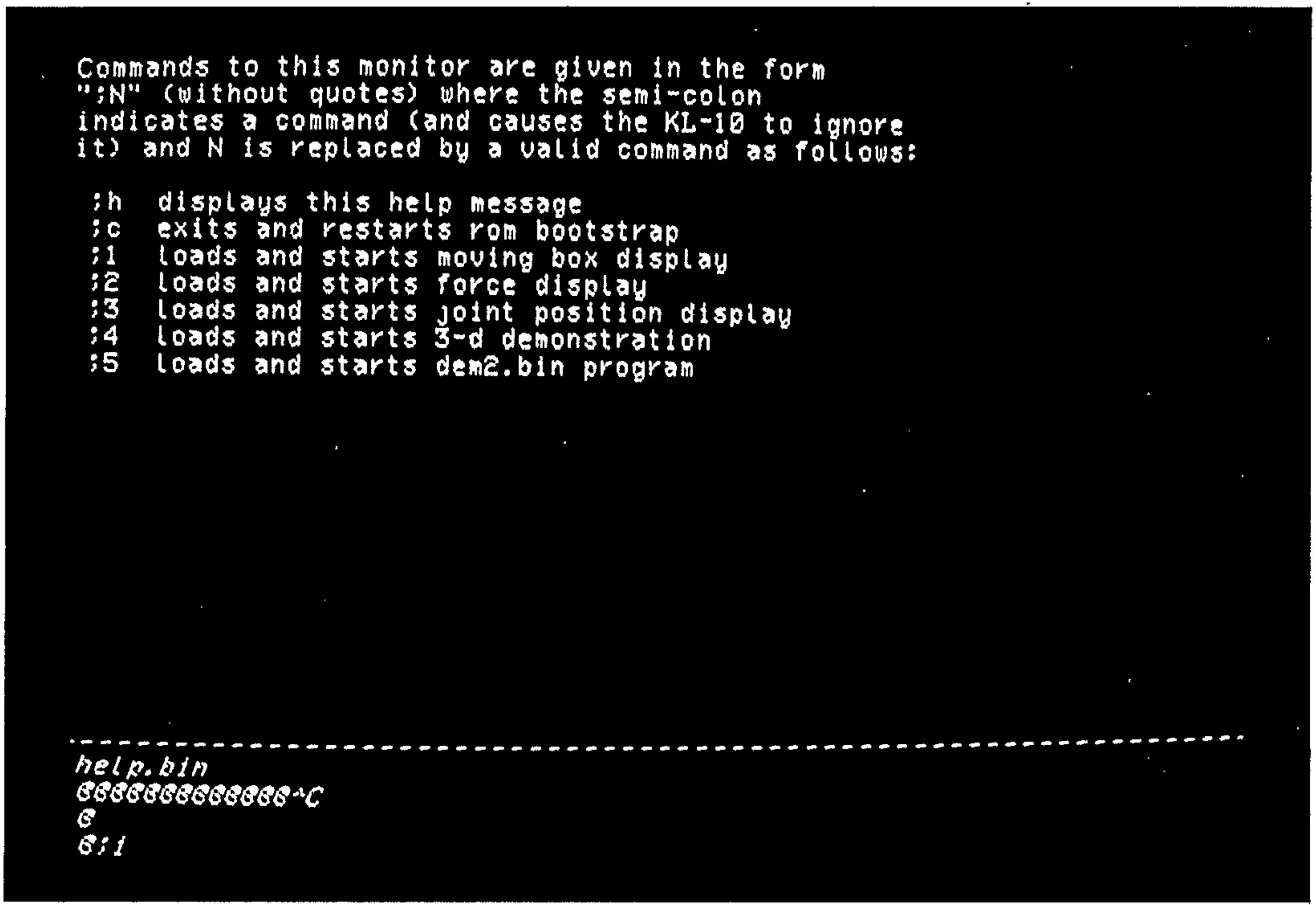


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FIGURE 33 COMMAND DEFINITION DISPLAY

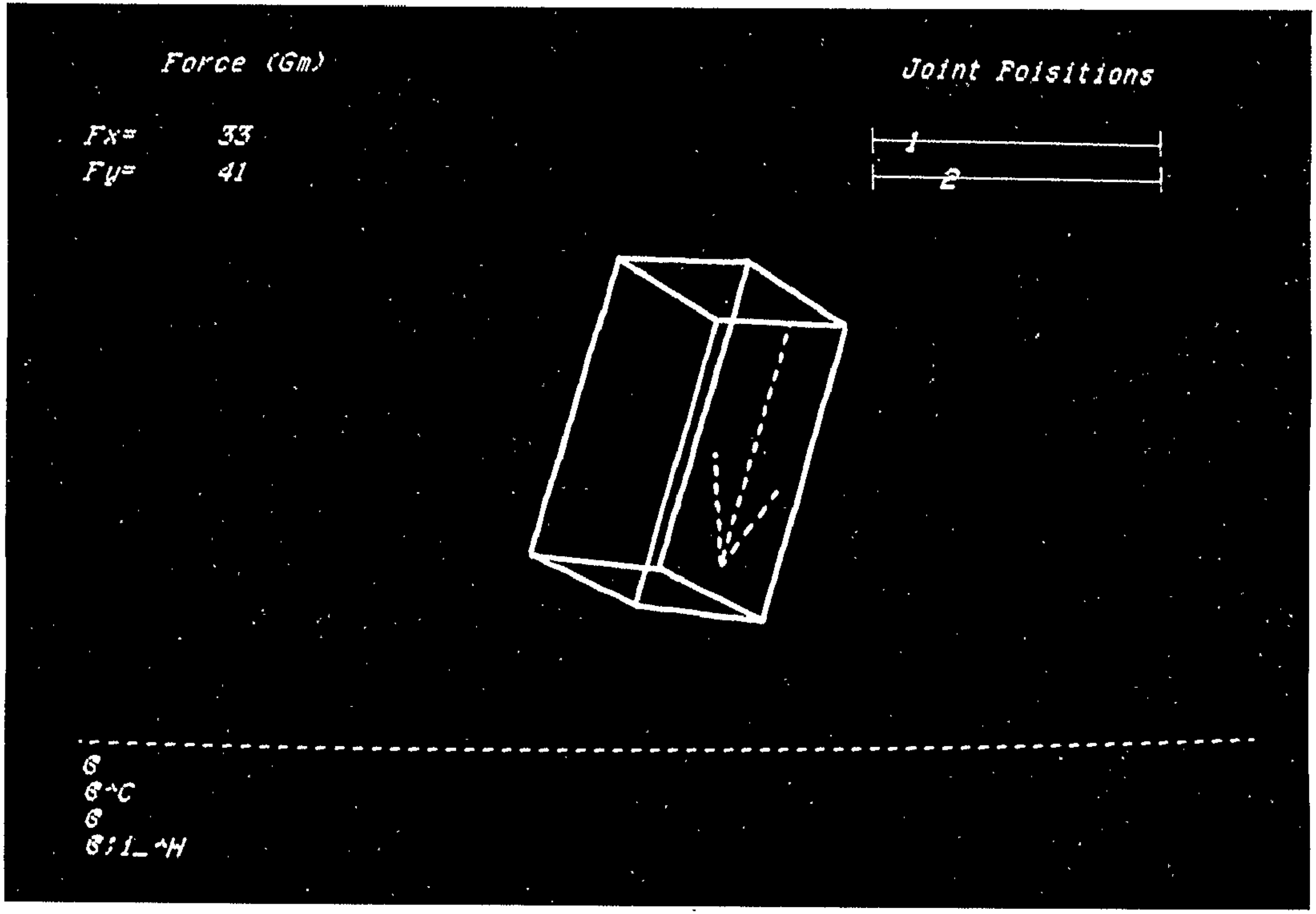

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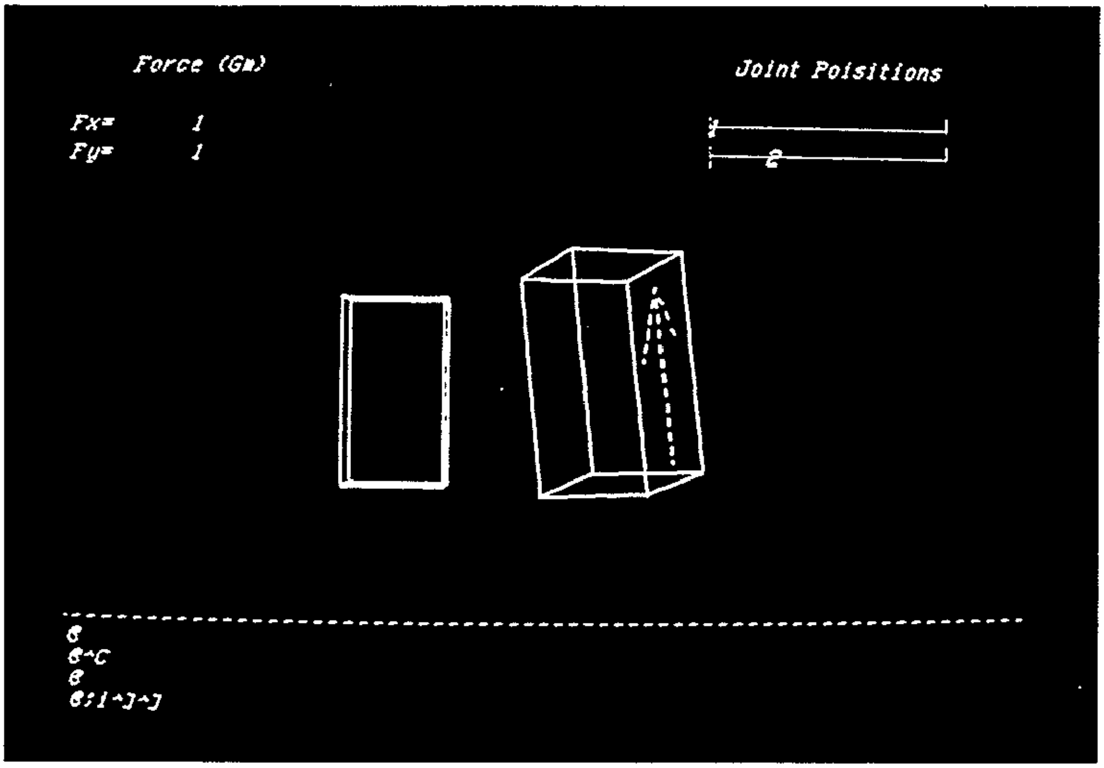
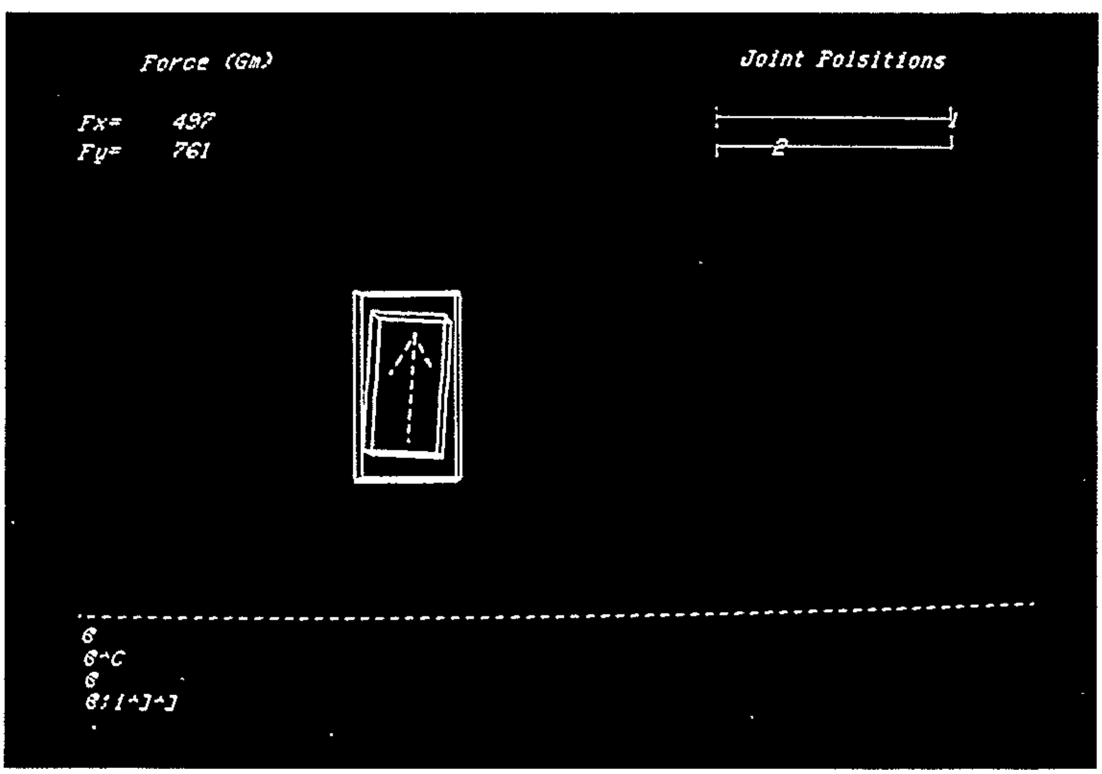
FIGURE 34 EXAMPLE OF TEXT, DIGITAL, ANALOGIC, AND PERSPECTIVE DISPLAYS



(a) MOVING RECTANGLE (RIGHT) OUTSIDE OF MARKER



(b) RECTANGLE POSITIONED INSIDE OF MARKER

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FIGURE 35 PLACEMENT OF CUBE

avoidance, velocity determination, target acquisition). By simply looking at the transformation matrices of two different objects, we may find the distance, d, between their origins to be

$$d = \left[(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)\right]^2 ,$$

where

$$\Phi_i = \begin{bmatrix} a_i & b_i & c_i & x_i \\ d_i & e_i & f_i & y_i \\ g_i & h_i & i_i & z_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1 = 1,2)$$

and the angles between the various basis bectors as

$$\theta_x = \cos^{-1}(a_1 * a_2 + d_1 * d_2 + g_1 * g_2) ,$$

$$\theta_y = \cos^{-1}(b_1 * b_2 + e_1 * e_2 + h_1 * h_2) ,$$

$$\theta_z = \cos^{-1}(c_1 * c_2 + f_1 * f_2 + i_1 * i_2) .$$

More detailed point-by-point comparisons could be made directly in world coordinates or by transforming the cube to target coordinates. The transformation relating cube points to the frame of reference fixed in the target is obtained by premultiplying the cube's object transform by the inverse* of the target's object transform:

---

*The inverse of a homogeneous matrix is relatively easy to compute:

$$\Phi = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_y & o_y & a_y & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} ,$$

(footnote continued on next page)

$$\Phi = \Phi_2^{-1}\,\Phi_1 \quad ,$$

where Φ_1 is the object transform given for the controller grip in the previous report[2] and Φ_2 is the object transform of the target. For a given static target, Φ_2^{-1} may be computed and used until the target is moved.

D. Display of Three-Dimensional Objects

1. Background

Displays for supervisory control (man-machine interaction) have been primarily based on printed messages or simulated instruments displayed on the screen of a cathode ray tube (CRT). Manipulation tasks entail operation in six dimensions--three displacements and three rotations. The feedback information for manipulation is inherently six-dimensional. We have been implementing a method to include such six-dimensional information on the supervisory display screen along with the usual text messages and two-dimensional graphic displays. The six-dimensional information is needed for several different purposes:

- Displaying the position and orientation of the manipulator along with the surrounding environment. This is the way prediction for inertial loads, arm springiness, and time delay can be included in the control system.
- Displaying the position and orientation of the end-effector.
- Force-feedback display (three forces and three torques).
- Range-sensor display oriented in hand coordinates.
- Tactile-sensor display oriented in hand coordinates.

---

where $\underline{n}$, $\underline{o}$, $\underline{a}$, and $\underline{p}$ are vectors; then

$$\Phi^{-1} = \begin{bmatrix} n_x & n_y & n_z & -\underline{p}\cdot\underline{n} \\ o_x & a_y & o_x & -\underline{p}\cdot\underline{o} \\ a_x & a_y & a_z & -\underline{p}\cdot\underline{a} \\ 0 & 0 & 0 & 1 \end{bmatrix} .$$

- Reconstruction of the external world scene based on range, force, and tactile information: a three-dimensional scene composed of each point ranged or touched during exploratory manipulations.

A general method for presenting perspective views of three-dimensional objects on the display screen has been implemented. The first use of this program will be to display two simple three-dimensional objects (cubes) for a tracking evaluation using rate and position controllers. In this evaluation, six-axis tracking (both step and compensatory tracking) will be investigated for the first time, enabling tracking models that were developed for pilots and drivers to be applied to manipulation.

2. Three-Dimensional Display on the GT-40

An item to be displayed is first described in a fixed image space. It is then transformed to object space using a series of homogeneous coordinate transforms (object transformation). A list suitable for immediate display by the display processor is created by the view transform, which includes a perspective transform. This process is illustrated in Figure 36. Displayed objects may include various combinations of solid and dashed lines and intensities.

Rigid bodies to be displayed on the GT-40 are initially described in an image reference frame (Frame C in Figure 37). After undergoing a series of transformations (scaling, rotation, and translation), together called the object transform (θ), each image point is placed into the object reference frame (Frame B of Figure 37). Several differently transformed images may be concatenated to build the object. The object points are then subjected to a series of translations and rotations together called the view transform (V), to place the object into world coordinates (Frame A of Figure 37). The world origin (O) is fixed in the center of the CRT screen with the X-axis to the right, the Y-axis up, and the Z-axis into the screen. Assuming the observer (E) to be located on the world m_z axis a distance Z_e from (O), we may use a simple perspective transform to project each world point P to screen coordinates (X_S, Y_S).

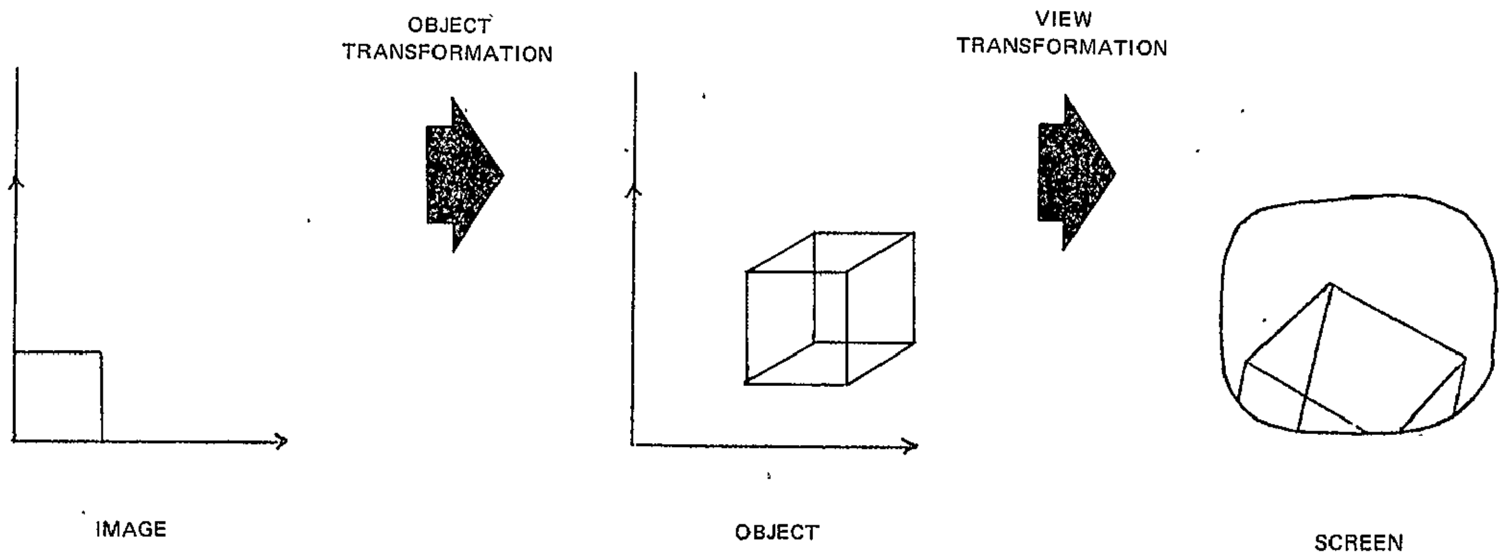

FIGURE 36 TRANSFORMATION PROCESS

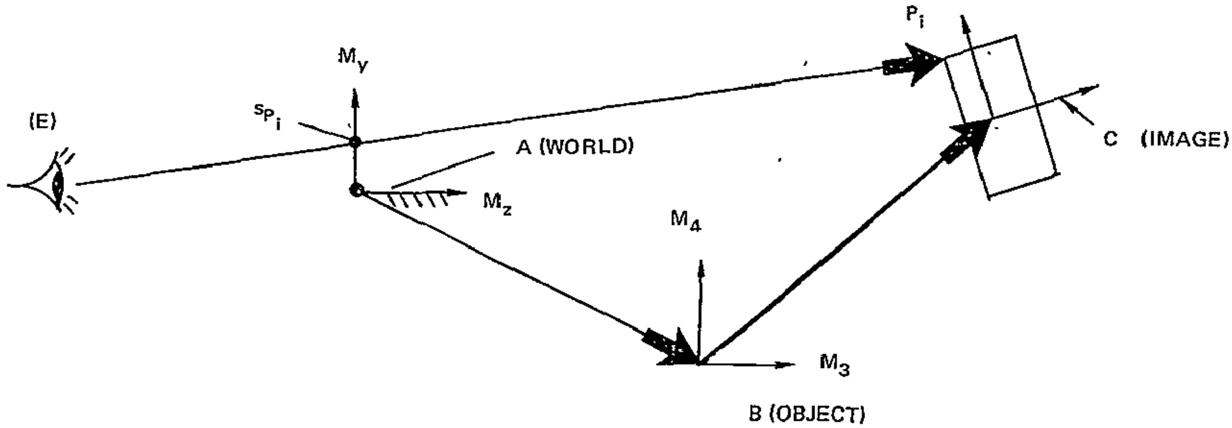

FIGURE 37 GEOMETRY OF DISPLAY GENERATION

Typically, the view transform is a constant transformation used to place the objects in the proper location relative to the observer. The object transform will usually vary from moment to moment reflecting changes in the command inputs. It will be used to make objects or elements of objects move in a prescribed manner.

In summary,

$$^{S}P_i = f_p\left\{[V][\theta]\,^{I}P_i\right\}$$

where

$$^{I}P_i = \begin{bmatrix} x_i \\ y_i \\ z_i \\ 1 \end{bmatrix} = \text{homogeneous coordinates of } P_i \text{ in image reference frame,}$$

$$^{S}P_i = \begin{bmatrix} x_i \\ y_i \end{bmatrix} = \text{screen coordinates of } P_i,$$

$f_p\{\quad\}$ = the perspective transform that yields screen coordinates from world coordinates,

$[V]$ = homogeneous view transform,

and

$[\theta]$ = homogeneous object transform.

Appendix A

PAPER PRESENTED TO THE
THIRTEENTH ANNUAL CONFERENCE ON MANUAL CONTROL

Massachusetts Institute of Technology
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TWO MEASURES OF PERFORMANCE IN A PEG-IN-HOLE MANIPULATION TASK WITH FORCE FEEDBACK*

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ABSTRACT

This paper describes the results from two manipulators on a peg-in-hole task, which is part of a continued effort to develop models for human performance with remote manipulators. Task difficulty is varied by changing the diameter of the peg to be inserted in a 50 mm diameter hole. An automatic measuring system records the distance between the tool being held by the manipulator and the receptacle into which it is to be inserted. The data from repeated insertions are processed by computer to determine task times, accumulated distances, and trajectories. Experiments with both the MA-11 cable-connected master-slave manipulator common to hot cell work and the MA-23 servo-controlled manipulator (with and without force feedback) are described. Comparison of these results with previous results of the Ames Manipulator shows that force feedback provides a consistent advantage.

INTRODUCTION

The task investigated in this paper is the peg-in-hole experiment previously examined by McGovern[1] and Hill.[2] The experiment board has been rebuilt to be more precise and to be incorporated into the measuring system. The experiment has been expanded to use three different moving distances (100, 200, and 400 mm) to provide a broader data base for the models.

Two manipulators were chosen for these experiments. The first was the French MA-11, a lightweight cable-connected manipulator designed for hot cell work. Similar to the Model 8 developed at Argonne Labs, it is

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representative of a large class of manipulators in use throughout the world in radioactive environments. With about 30,000 cable-connected manipulators in use in the world, they provide a standard for comparison with other types of manipulators. They offer the operator a low mass (5 kg) manipulation link to tasks with only six degrees of freedom. This link essentially removes the enormous dexterity and tactile sensibility of the human hand and limits the operator to motion and sensing with the six degrees of freedom provided.

The second manipulator chosen was the MA-23 force reflecting servo manipulator developed by the French Atomic Energy Commission (CEA). This manipulator system may be run with force feedback either turned on or off. It is one of about 20 manipulators in the world with this feature. An attempt was made to run the experiments with a similar American manipulator, the E-4 manipulator at Fermi National Accelerator Laboratory, Batavia, Illinois, but it was not operational at the time scheduled for the experiment. Manipulators with force feedback capability were sought to characterize the changes in performance attributable to force feedback.

The performance measuring system is based on a tensioned string that measures the distance between the tip of a tool and a receptacle into which the tool is to be inserted. The string also permits the progress into the hole to be monitored as the tool is inserted. From records of string length as a function of time, tool trajectories as well as velocities and task times can be determined. The system makes a permanent record of the string length 25 times a second as the tool is moved to and into the receptacle.

PORTABLE DATATAKER

A portable data collection system was designed and constructed to obtain and compare performance of different teleoperators. The system measures the distance from a tool to a receptacle in which the tool is to be inserted. The datataker records the distance between the end of the tool and the bottom of the receptacle as a function of time. This distance is measured by a dacron string of low extensibility to the nearest 2 mm and is punched on paper tape at the rate of 25 measurements/sec. The range is calibrated from 0 to 510 mm in 256 steps (8 bits).

The entire experimental arrangement is shown in Figure 1. The experimenter operates the tape perforator, while the subject manipulates

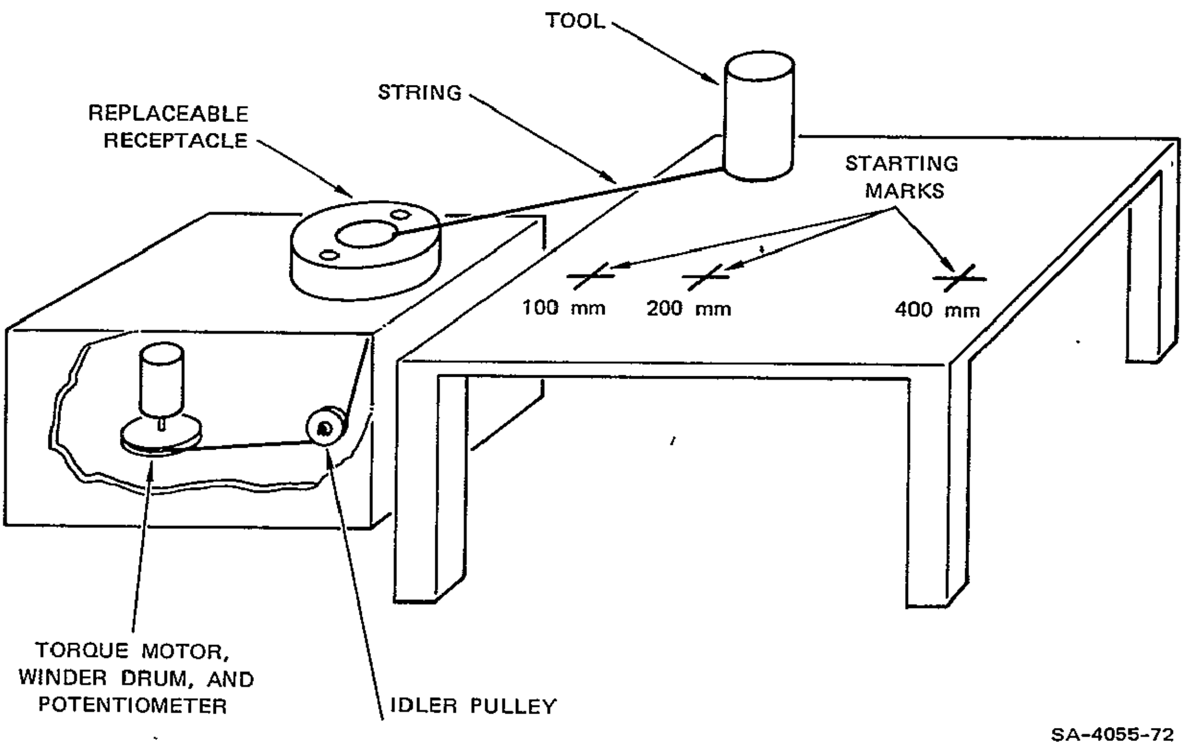

FIGURE 1 TASK CONFIGURATION WITH MEASURING UNIT AND ACCESSORY TABLE

the tool. The measuring string connects the tool and the string puller. This system is similar to that previously described[2] for measuring the X, Y, and Z coordinates of the manipulated tool, except that a single string is used. This simplification in measuring was suggested by the results of two previous studies using a more sophisticated datataker.[1,3] In these studies the distance between hole and tool as a function of time was the most important parameter in explaining the experimental results. This measurement could be used to divide the task into different therbligs and to proportion a fixed amount of time for each one. Detailed descriptions of the equipment including dimensions of the task boards and operation of the datataker are given in a technical report.[4]

A data reduction program reads the paper tapes and makes a set of measurements on the trajectories. The measurements, a sample of which is shown in Figure 2, are briefly described below:

<u>Reaction Time</u>--Reaction time is the time after the experimenter turns on the punch, which is the audible signal for the subject to begin, until the subject pulls the string 4 mm from its initial length (time zero).

<u>Zero Length</u>--Zero length is the string length when the tool is at the entrance to the receptacle. This length is determined from the calibration recordings.

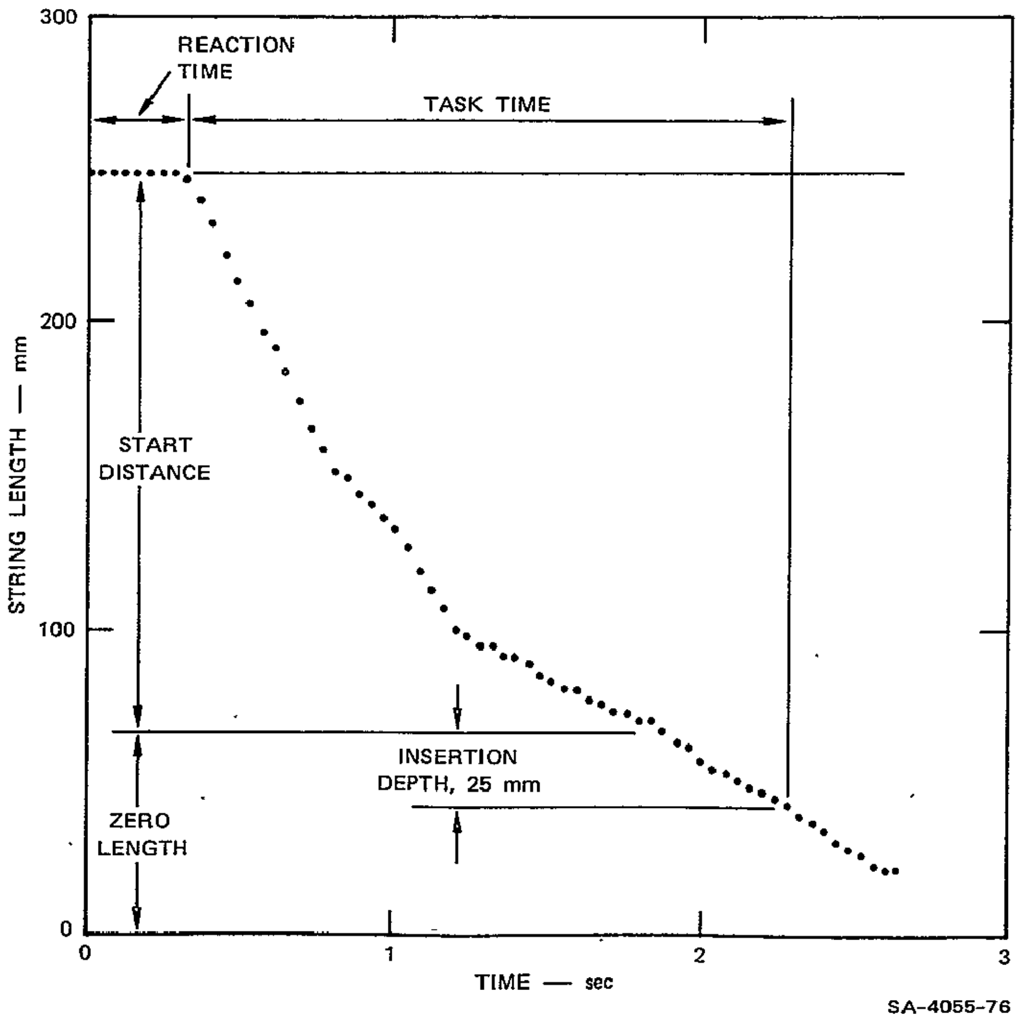

FIGURE 2 SAMPLE TRAJECTORY MEASURED BY DATATAKER

Start Distance--Start distance is the difference between the string distance at time zero and zero length as defined above.

Task Time--Task time is the time from when the tool is first moved until it has been inserted 25 mm into the receptacle.

In addition to these parameters, the first times to a set of given distances from the hole entrance are determined in order to plot the average trajectory. The set of distances are: 350, 300, 250, 200, 150, 100, 90, 80, 70, 60, 50, 40, 30, 20, 10, and 0 mm from the hole and 10, 20, 25, and 30 mm into the hole.

PEG-IN-HOLE EXPERIMENT

The object of the task was to insert a set of pegs into a round receptable. The difficulty of the experiment was varied by using pegs of different diameter. The experimental apparatus is basically the same as that used by McGovern.[1] The same pegs were used but a more precise receptacle was installed on the taskboard. Tool trajectories were recorded as a function of time, using the data acquisition system.

Manipulators

Two different manipulators were chosen for use in the experiment: a lightweight master-slave manipulator (MA-11) of the family used for hot cells and a heavy duty servo manipulator (MA-23) that has more general purpose use. These manipulators are shown in Figures 3 and 4. Technical descriptions including dimensions, load capability, speed, and backlash for the MA-11 and MA-23, respectively, are given in a technical report.[4] Both manipulators were developed by the French Atomic Energy Commission at Saclay, France, for radioactive handling by Dr. Jean Vertut's Environmental Protection group.[5,6]

Experimental Design

The basic experiment consists of the 7 × 3 × 8 factorial design shown in Figure 5. For each distance and peg combination, eight insertions of the peg into the receptacle were made. Seven pegs were used (Pegs 2, 4,

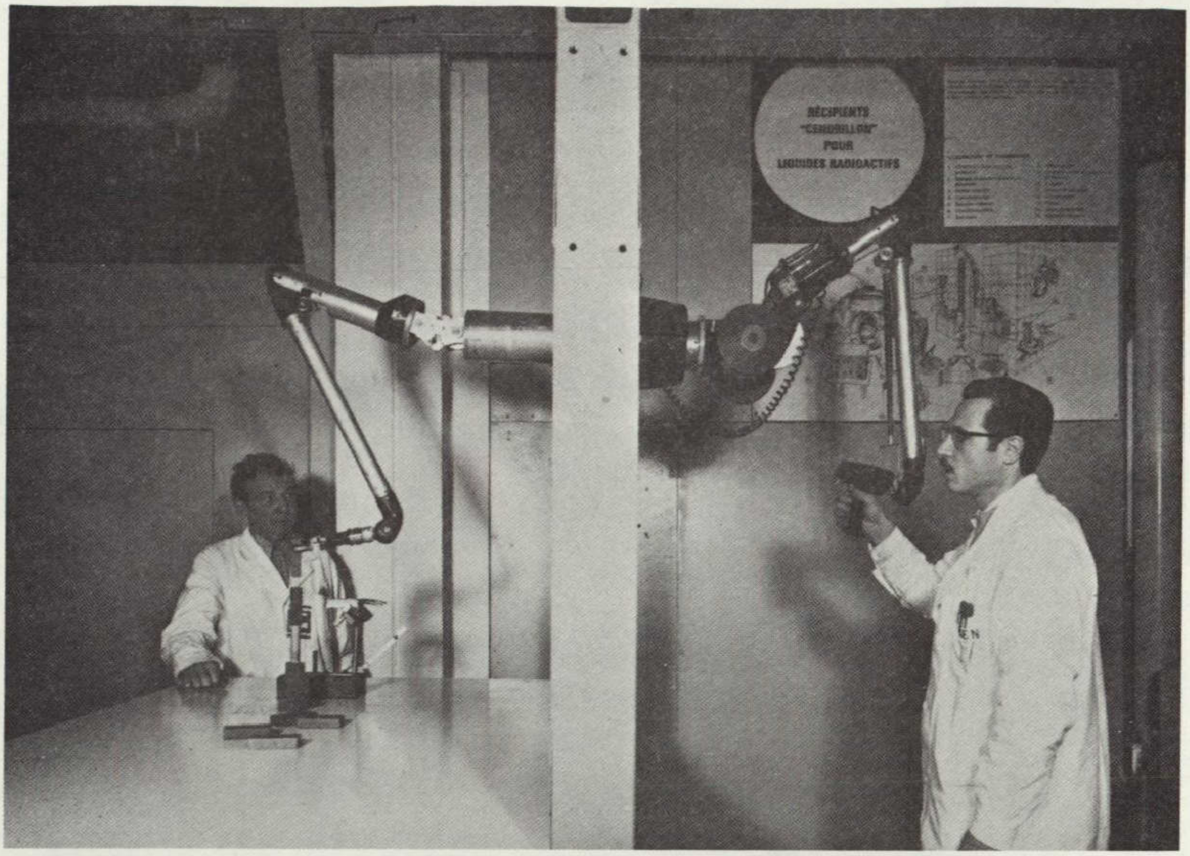

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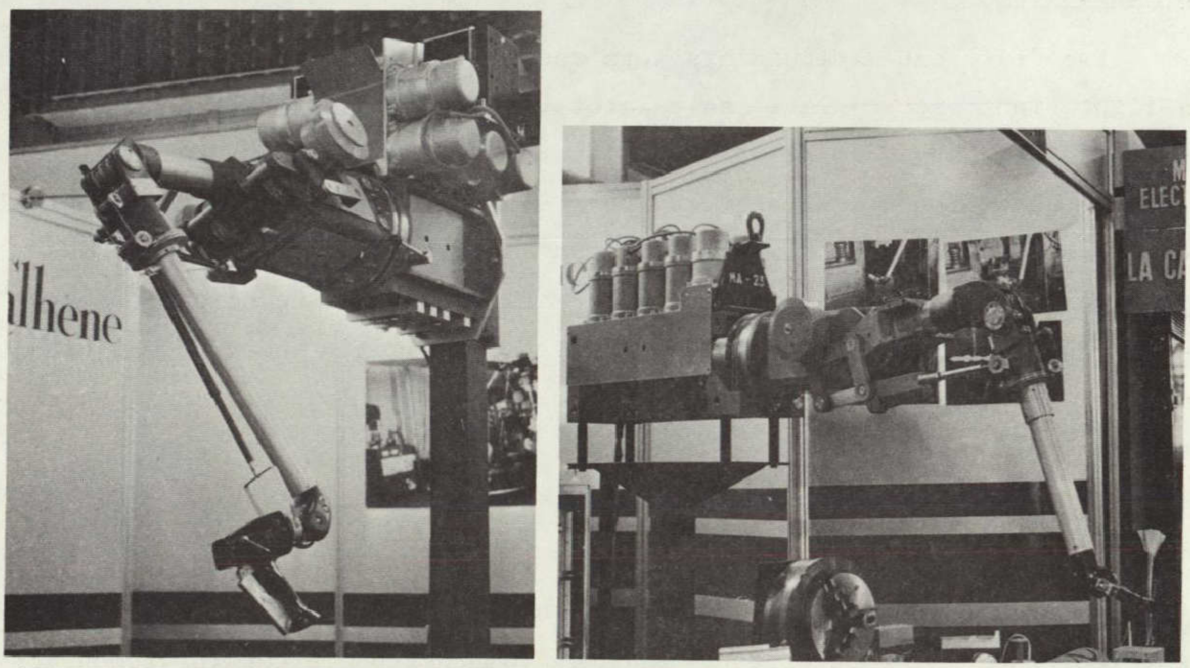
FIGURE 3 MA-11 CABLE-CONNECTED MASTER-SLAVE MANIPULATOR



(a) MA-23 FORCE-REFLECTING MASTER (5 kg)

(b) MA-23/200 HEAVY DUTY SLAVE (25 kg)

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FIGURE 4 MA-23 SERVOMANIPULATOR

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two, and switched on the punch, which had a distinct noise. When the subject heard the noise, he proceeded to move the tool into the receptacle. When the tool tip disappeared inside the receptacle (about 50 mm) the experimenter turned off the punch and the subject returned the tool to the starting mark to prepare for the next insertion.

MA-11 RESULTS

The peg-in-hole experiment was run with two subjects in the manner previously described and the resulting trajectories analyzed by computer program to obtain task times and details on the trajectories. Task completion time is defined as the time from the beginning of the move until the tip of the tool is inserted 25 mm into the receptacle. At this point the tool is first inside the 25 mm thick receptacle, and the angular and translational degrees of freedom are constrained as determined by the geometry of the tool and receptacle.

Basic task times for the peg-in-hole task are shown in Figure 6. These times increase as the difficulty of the task (peg number) increases. Differences between the three trajectory lengths appear to be constant, all three increasing with peg number. This suggests that the times are accounted for by the sum of two functions; one a function of trajectory length, the other a function of peg number (difficulty).

Since the precision of fit of each peg is double that of the preceding one, the abscissa on Figure 6 is also a measure of task difficulty as defined by Fitts.[7] An interesting feature of the results is their upward curvature: task time is an accelerating function of difficulty, whereas Fitts law predicts a linear function of difficulty. Analyses of variance were performed on the total task times to obtain the statistics for testing hypotheses about these functions.

Task time is a strong function of the peg number [$F(1,294) = 56.49$, $p < 0.001$] and is nonlinear [$F(4,294) = 12.4$, $p < 0.001$]. Task time is also a strong function of the trajectory length [$F(2,294) = 43.80$, $p < 0.001$] but there is insufficient evidence to show that it is nonlinear [$F(1,294) = 0.05$, $p > 0.05$]. The interaction between peg and trajectory

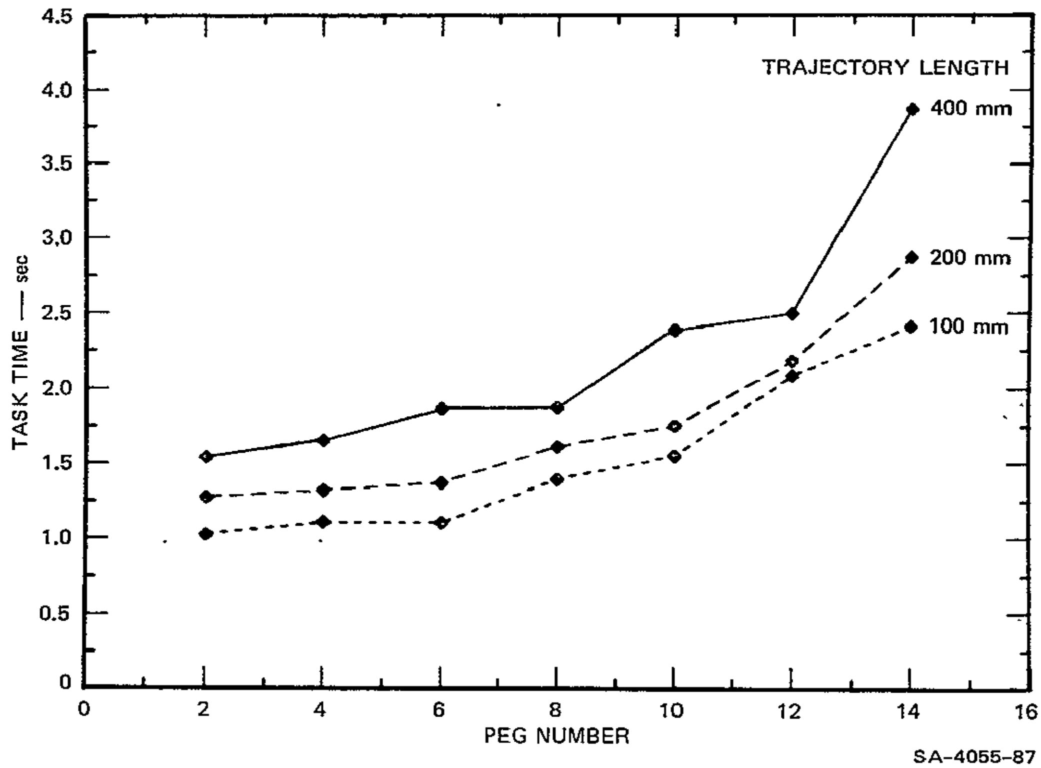

FIGURE 6 MA-11 TASK COMPLETION TIMES

length [$F(12,294) = 1.69$, $p > 0.05$] is not statistically significant, suggesting independence between these two parameters. With this information we can assume the following model for this task:

$$\text{Task time} = f_1(\text{peg}) + K_1(\text{trajectory length}) \qquad (1)$$

where f_1 is an accelerating function of the peg number and K_1 is a linear function of trajectory length.

Trajectories for Pegs 2, 8, and 14 are shown in Figure 7. The trajectories show a transition between the smooth insertions with Peg 2 to the two-stage insertion with Peg 14, where the insertion is practically stopped at the entrance to the hole. Similar transitions between smooth and two-stage insertions were observed in previous experiments[1,2] as the task difficulty was increased. Note that the initial trajectories for the three pegs shown in Figure 7 have the same slope even though the scale change makes it appear that Peg 14 is inserted faster.

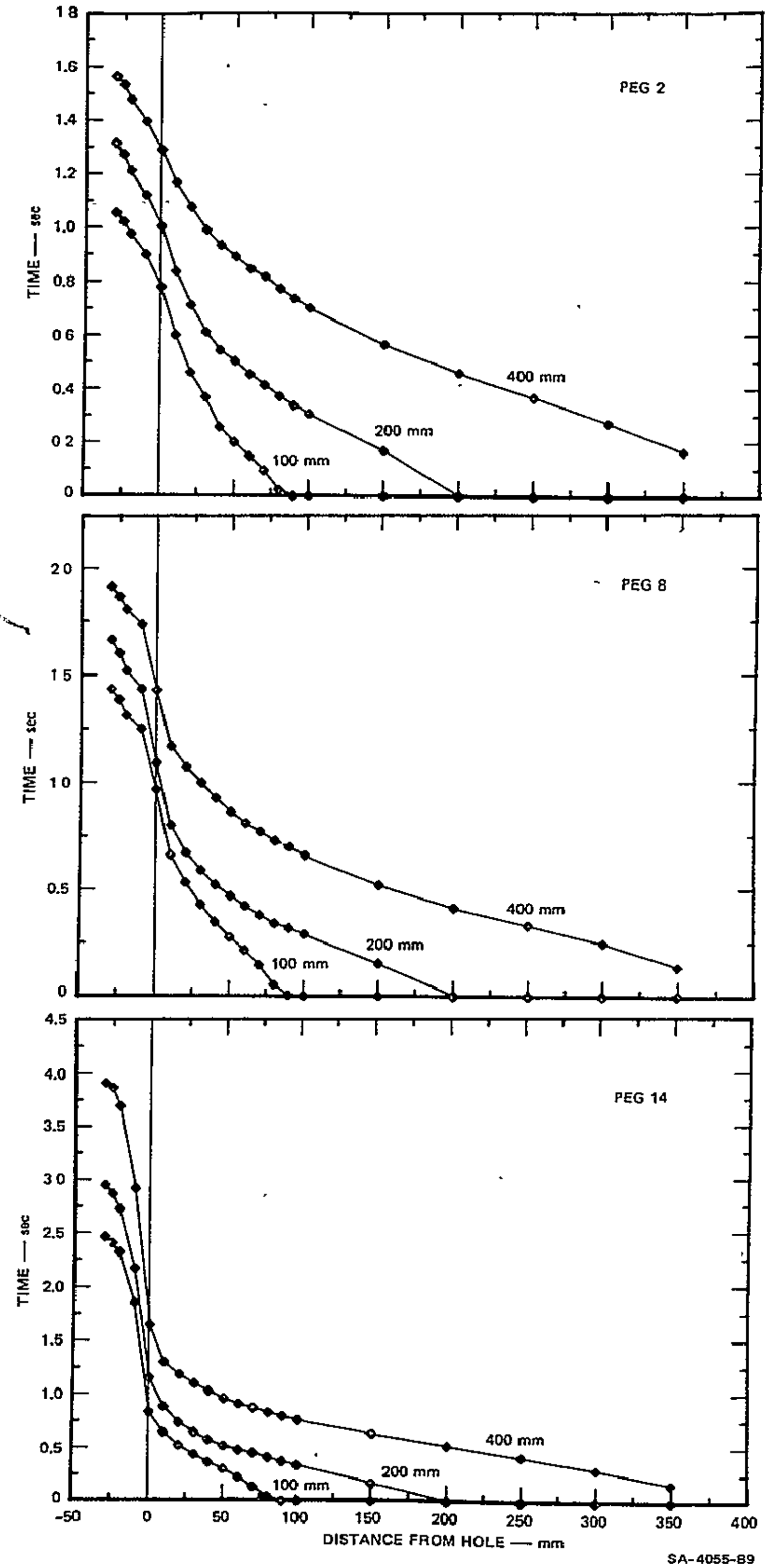

FIGURE 7 MA-11 TRAJECTORIES WITH INCREASINGLY DIFFICULT PEGS

MA-23 RESULTS

In part of a program to determine the advantages of force feedback in different manipulation tasks, the Peg-in-hole task was run on an MA-23 manipulator with and without force feedback. The comparison was made with two subjects who served in both the force and no-force conditions. The experiment was balanced for practice effects by starting one subject on the force and the other on the no-force condition and running the two through the design in reverse directions.

The task times shown in Figure 8 are of the same shape as those of the MA-11. Generally, the MA-23 is 30 to 40% slower without force feedback than with it. There are no distinctive changes as the peg number increases except for the most difficult peg (Peg 14). Here the insertion time is doubled when force feedback is removed.

An analysis of variance of the MA-23 task times shows that times with force feedback are significantly shorter than without it [$F(1,588 = 129$, $p < 0.001$]. Task completion times are also strong functions of the peg and the trajectory length, both being statistically significant at the 0.001 level. Task completion times are nonlinear functions of the peg number, as with the MA-11, because the nonlinear term is statistically significant at the 0.001 level [$F(5,588) = 19.16$, $p < 0.001$]. The nonlinear term in the trajectory length [$F(1,588) = 0.19$, $p > 0.05$] is not significant, indicating that, again, the time is a linear function of trajectory length. Of the three interactions, force feedback and peg number interact significantly ($p < 0.001$), whereas force feedback and trajectory length do not ($p > 0.05$), and peg number and trajectory length do not ($p > 0.05$). These results indicate that there are two models for MA-23 performance in this task. With force feedback we have

$$\text{Task time} = f_f(\text{peg}) + K_2(\text{trajectory length}) \qquad (2)$$

and without force feedback we have

$$\text{Task time} = f_{\bar{f}}(\text{peg}) + K_2(\text{trajectory length}) \qquad (3)$$

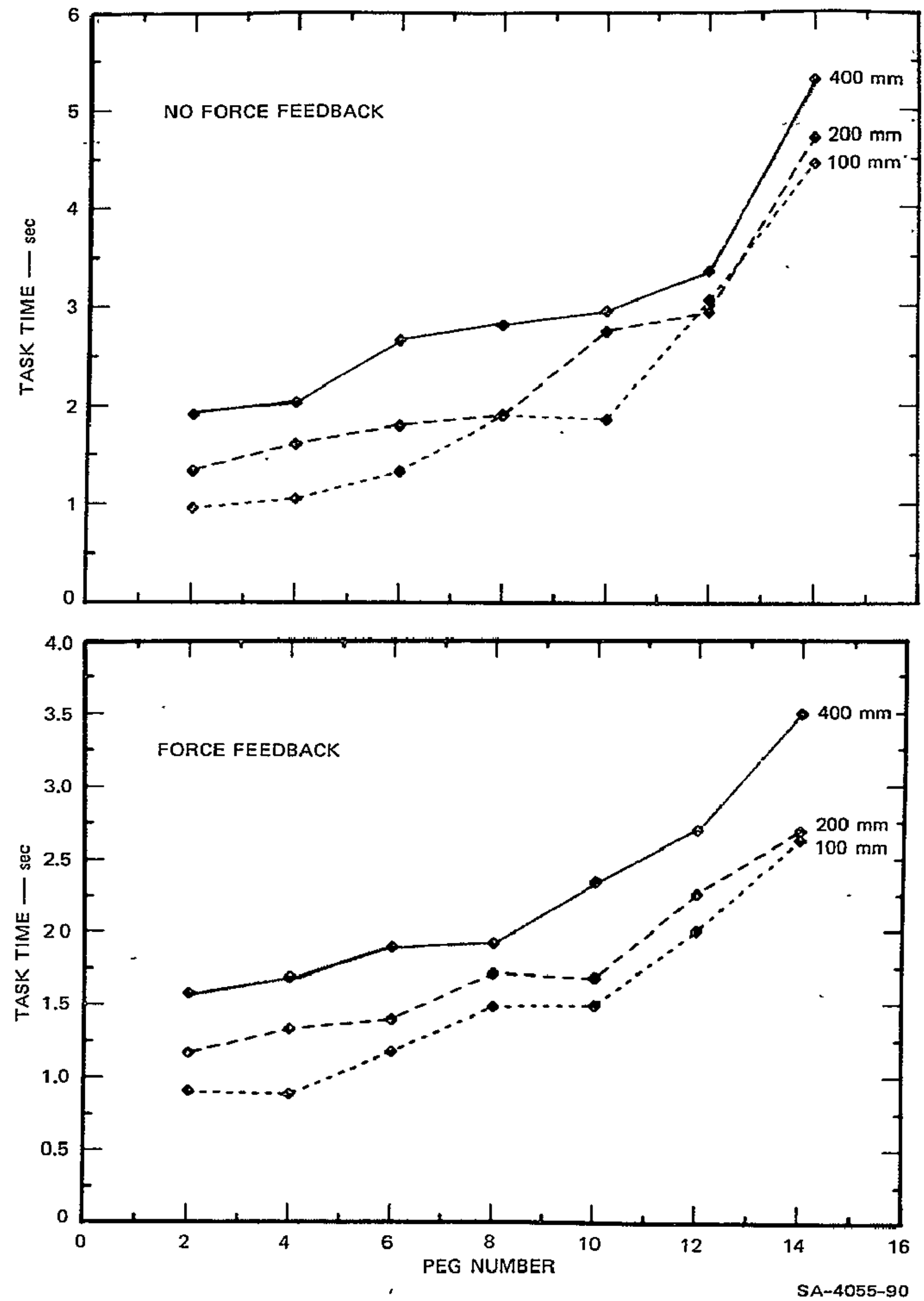

FIGURE 8 COMPARISON OF TASK COMPLETION TIMES WITH AND WITHOUT FORCE FEEDBACK

where the two curving functions, f_f and $f_{\bar{f}}$ of peg size are different, and the linear functions of K_2 of trajectory length are identical.

The trajectories shown in Figure 9 also indicate the general reduction in task time with force feedback. There is a slowing down near the receptacle entrance (between 0 and 10 mm from receptacle) when force feedback is absent, and the insertions take about twice as long without force feedback as with it. The general increase in time without force feedback is apparent throughout the results; gross trajectories as well as fitting movements require more time. With the shortest trajectory (100 mm from the receptacle) gross motion and fitting are intertwined, and it may be impossible to separate these motions (or therbligs) from the data without a model.

SUMMARY

The formulation for the peg-in-hole task with the two manipulators (Equations 1, 2, and 3) shows that task time is a sum of two independent functions--a nonlinear function of peg number and a linear function of trajectory length.

Task times as a function of peg are illustrated in Figure 10 for several situations. Shown are data from the 400-mm trajectories performed with the MA-11 and MA-23 taken from this experiment and data from McGovern[1] (406 mm trajectories) using the Ames Arm and the unaided human hand. The same set of pegs was used in each experiment. Nearly identical functions were obtained under the two force feedback and the two no force feedback conditions, although different manipulators and test subjects were used. Two functions explain the results of all the manipulators: one for force feedback (f_1, from Equation 1, and f_f from Equation 2), the other for no force feedback ($f_{\bar{f}}$ from Equation 3). It thus appears that the task time can be predicted from the geometry of the task (peg number) and the presence or absence of force feedback.

Task times as a function of trajectory length are shown in Figure 11. The linearity of the results as well as the similarity of the two force feedback conditions are obvious for the MA-11 and MA-23 (no force

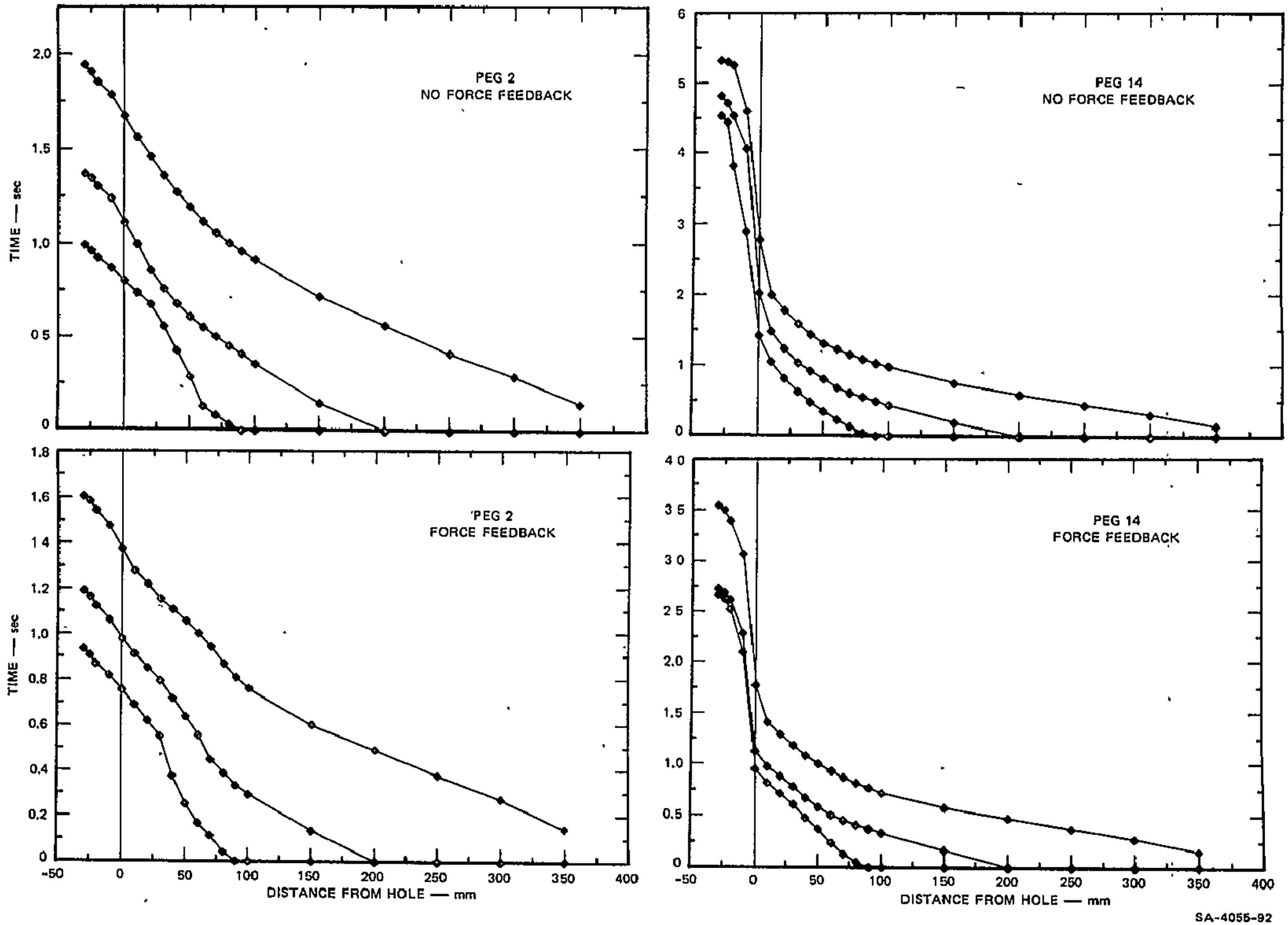

FIGURE 9 COMPARISON OF MA-23 TRAJECTORIES WITH AND WITHOUT FORCE FEEDBACK

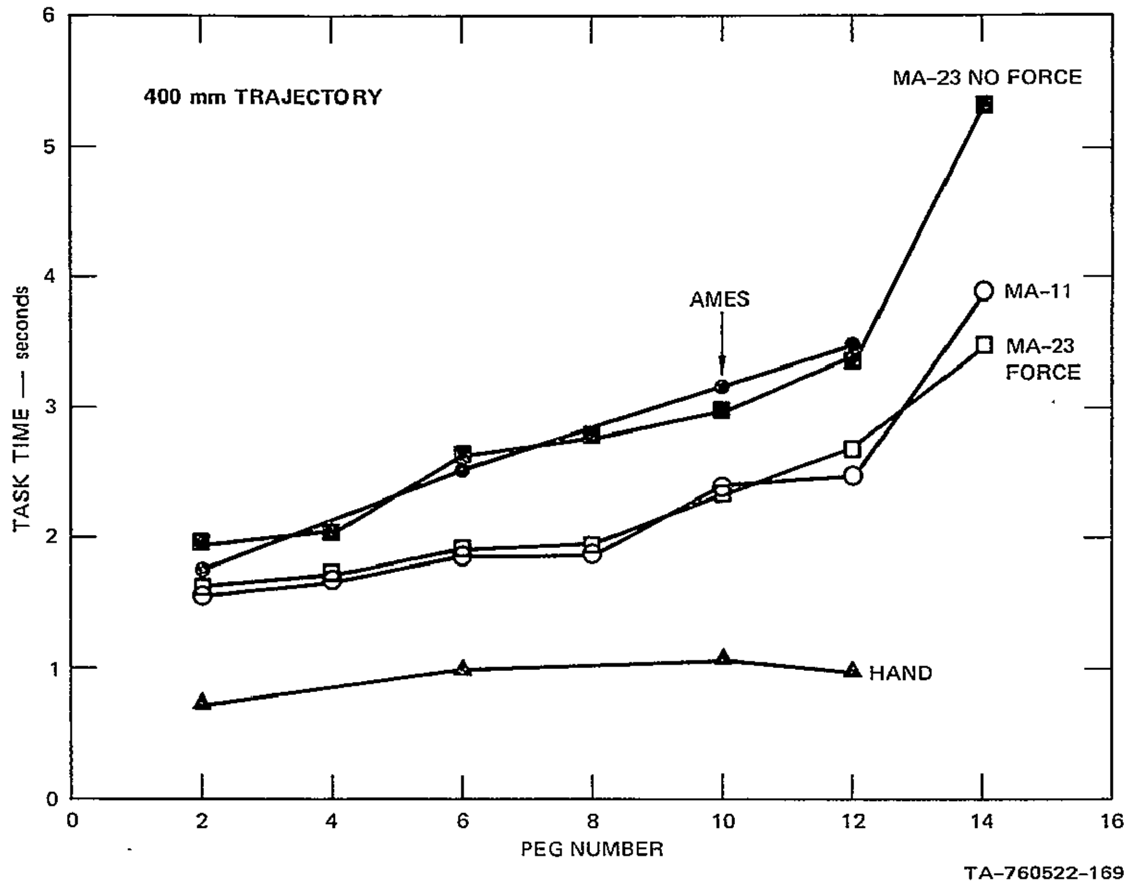

FIGURE 10 TASK TIMES FOR FIVE DIFFERENT PEG-IN-HOLE EXPERIMENTS

feedback) experiments. A statistical analysis of the results indicates that there is insufficient evidence to show that the slopes of the two lines are different [$F(1,488) = 1.76$, $p > .05$]. This suggests that a common linear function describes the trajectory times of the task for both manipulators (K_1 from Equation 1 equals K_2 from Equations 2 and 3).

In conclusion, the functions for peg number and trajectory length offer a mathematical basis that there are two independent parts of the task, a trajectory part and a fitting part, which substantiate the results of Hill and Matthews[3] with a degree-of-constraint task, and the industrial time-and-motion studies with additive transport and positioning times. These results do not agree with Fitts' Law,[4] which assumes an inverse relation between trajectory length and precision. Thus, the distance moved and the type of force feedback appear to be basic measures of manipulator performance, independent of manipulator.

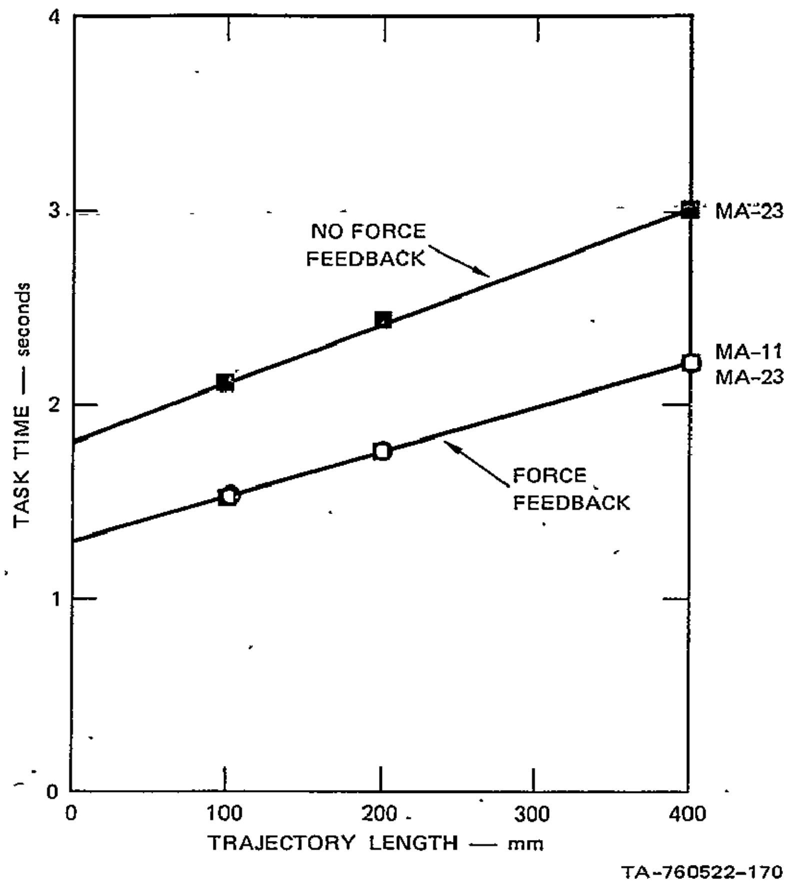

FIGURE 11 AVERAGE TASK TIME VERSUS TRAJECTORY LENGTH

REFERENCES (Appendix A)

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4. J. W. Hill, "Study to Design and Develop Remote Manipulator Systems," Quarterly Reports 5 and 6 combined, Contract NAS2-8652, Stanford Research Institute, Menlo Park, California (January 1977).

5. Société La Calhène, "Use of the Electronic Master-Slave Manipulator MA-23 in Reprocessing and Vitrification Facilities," Manual No. 43, Bezons, France (May 1976).

6. J. Vertut, J. Charles, P. Coiffet, and M. Petit, "Advance of the New MA-23 Force Reflecting Manipulator System," Paper presented at the RoManSy-76 Symposium, Warsaw, Poland, 14-17 September 1976 (Proceedings will be published through CISM in 1977).

7. P. M. Fitts, "The Information Capacity of the Human Motor System in Controlling Amplitude of Movement," Journal of Experimental Psychology, Vol. 47, pp. 381-391 (1954).

Appendix B

COMPUTER PROGRAM FOR REDUCING PAPER TAPE DATA

```
      PROGRAM PFORM(TAPE1,OUTPUT,TAPE2=OUTPUT)
C     PFORM   11/27/76      J.W. HILL
C
C     MAIN PROGRAM TO OBTAIN PERFORMANCE DATA FROM
C     PAPER TAPE RECORDINGS
CONSTANTS FOR NIN SUBROUTINE
      INTEGER IPTR,TDATA(16)
      COMMON IPTR,TDATA,NLINES
C
CONSTANTS FOR MAIN PROGRAM
      INTEGER TRAJ(400)
      INTEGER ZERO,ZFLAG,COND,SUBJ,RUN,EXP
      INTEGER RT,SDIST,TRAJ1,TSUM,TDIF
      INTEGER TIME(20),LTIME,RTDIST,TDIST,NLOW
      INTEGER DIST(20)
      DATA DIST /350,300,250,200,150,100,
     1 90,80,70,60,50,40,30,20,10,0
     2 ,-10,-20,-25,-30/
      LTIME=20
      IPTR=0
      ZERO=0
      ZFLAG=0
      COND=0
      EXP=0
      SUBJ=0
      RUN=0
      NLINES=0

C
C
C     STARTING POINT -- INPUT A STRING
C
100    CALL SIN(TRAJ,NCHR,NCOIN,NINC,NDEC,NBAR)
      MCHR=4
      MDEC=12
      MCOIN=1
C     IS IT A ZERO SET (EXP 300)↓
      IF(ZFLAG.EQ.1) GOTO 140
C     IS IT LONG ENOUGH↓
      IF(NCHR.LT.MCHR) GOTO 120
C     IS IT A CONSTANT ↓
      IF((NCHR-NCOIN).LE. MCOIN) GOTO 300
C     IS IT A TRAJECTORY ↓
      IF(NDEC.GT.MDEC) GOTO 400
C     ITS NONE OF ABOVE.
      WRITE(2,110)MCOIN,MDEC
110   FORMAT(* STRING NOT CONSTANT, NCHR-NCOIN .LE.*,
     1 I3,/* STRING NOT TRAJ, NDEC.GT.*,I3)
      GOTO 200
120   WRITE(2,130)MCHR
130   FORMAT(* STRING TOO SHORT, NCHR.LT.*,I3)
      GOTO 200
140   ZERO=NBAR
      WRITE(2,150) NBAR
150   FORMAT( * ZERO =*, I3)
      ZFLAG=0
      GOTO 100
200   CONTINUE
C
C     ERROR INDICATION - - -
C     OUTPUT THE COUNTS AND THE DATA STRING
C
      WRITE(2,220) NCHR,NCOIN,NINC,NDEC,NBAR
220   FORMAT(1X,I6,* CHR*,I6,* COIN*,I6,* INC*,I6,* DEC*,I6,*=BAR*,
     1 *     LINE*,I5)
      WRITE(2,230)(TRAJ(I),I=1,NCHR)
230   FORMAT(20(1X,O3))
      GO TO 100
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C
C
C     STRING IS PRETTY CONSTANT
C
300   CONTINUE
C IS IT A RUN↓
      IF(NBAR.GT.0.AND.NBAR.LT.16) GOTO 320
C IS IT A CONDITION↓
      IF(NBAR.GE.64 .AND. NBAR.LT.128) GOTO 330
C IS IS A SUBJECT↓
      IF(NBAR.GE.128 .AND. NBAR.LT. 148) GOTO 340
C IS IT A CALIBRATION↓
      IF(NBAR.EQ.192) GOTO 350
C IS IT AN EXPERIMENT↓
      IF(NBAR.GT.192 .AND. NBAR.LT.202) GOTO 360
C ITS NONE OF ABOVE↓
      WRITE(2,310) NBAR
310   FORMAT(1X,I3,* NOT A PERMITTED CONSTANT*)
      GOTO 200
320   RUN=NBAR
      GOTO 100
330   COND=NBAR-64
      GOTO 100
340   SUBJ=NBAR-128
      GOTO 100
350   ZFLAG=1
      GOTO 100
360   EXP=NBAR-192
      GOTO 100
C
C     STRING LOOKS LIKE A TRAJECTORY
C
400   CONTINUE
C
C   DETERMINE REACTION TIME (RT IN 25 THS OF SECOND)
C    AND STARTING DISTANCE( SDIST IN MM)
C
C     BY PEELING OFF CONSTANT NUMBERS .
C
      MRT=2
      TRAJ1=TRAJ(1)
      TSUM=TRAJ1
      DO 410 I=2,NCHR
      TDIF=TRAJ1-TRAJ(I)
      IF(TDIF.GT.MRT) GOTO 425
      TSUM=TSUM-TDIF+TRAJ1
410   CONTINUE
      WRITE(2,420) MRT
420   FORMAT(* BAD TRAJ, NO CHANGES .GT.*,I3)
      GOTO 200
425   RT=I-1
      SDIST=(TSUM+TSUM+TSUM+TSUM+RT)/(RT+RT) - ZERO-ZERO
C
C  ZERO TIME ARRAY
C
      DO 430 I=1,LTIME
430   TIME(I)=0
C
C     SEARCH THROUGH DISTANCE ARRAY TO FIND
C           FIRST APPROPRIATE DISTANCE
C
      RTDIST=2*(TRAJ(RT)-ZERO)
      DO 440 I=1,LTIME
      IF(DIST(1).LE.RTDIST) GOTO 450
440   CONTINUE
      WRITE(2,445) RTDIST,RT,SDIST
445   FORMAT(* BAD TRAJ, RTDIST=*,I3,* TOO SMALL*/
     1  I6,*=RT*,I6,*=SDIST*)
      GOTO 200
450    CONTINUE
```

```
C
C         FILL IN TIME TABLE
C
      NLOW=RT
      DO 480 J=I,LTIME
      TDIST=DIST(J)
C
      DO 460  K=NLOW,NCHR
      IF((TRAJ(K)-ZERO)*2.LE. TDIST) GOTO 470
460   CONTINUE
C  ERROR HANDELING
      WRITE(2,465)TDIST
465   FORMAT(* AT END OF TRAJ, DID NOT GO BELOW*,I3,* MM*)
      DO 468 JJ=J,LTIME
468   TIME(JJ)=NCHR-RT
      GOTO 490
C   END OF TRAJ ERROR
470   NLOW=K
      TIME(J)=K-RT
480   CONTINUE
490   CONTINUE
C
C
C         OUTPUT THE DATA
C
C
      WRITE(2,500)EXP,SUBJ,COND,RUN,RT,SDIST,(TIME(I),I=1,LTIME)
500   FORMAT(I2,*E*,I2,*S*,I2,*C*,I2,*R *, 22I3)
      GOTO 100
      END
```

```
C     INPUTS A SINGLE NUMBER FROM INPUT FILE
C
      SUBROUTINE NIN(X)
      INTEGER X,TDATA(16),PTR
      COMMON PTR,TDATA,NLINES
      NMAX=16
      IF(PTR.GT.0.AND.PTR.LT.NMAX) GO TO 100
      NEOF=1
40    READ(1,50)(TDATA(I), I=1,NMAX)
50    FORMAT(03, 15(04))
      IF(EOF(1).NE.0) GOTO 150
      NLINES=NLINES+1
      PTR=0
100   PTR=PTR+1
      X=TDATA(PTR)
      RETURN
150   WRITE(2,155) NLINES
155   FORMAT(* EOF --------------*,I6,* LINES READ*)
      NEOF=NEOF+1
      IF(NEOF .GT. 10) STOP 1
      GOTO 40
      END
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      SUBROUTINE SIN(TRAJ,NCHR,NCOIN,NINC,NDEC,NSUM)
      INTEGER TRAJ(1)
      INTEGER X,XL,XT
C
C  SUBROUTINE TO PLACE A LINE OF NUMBERS SEPERATED
C  BY ZERO INTO ARRAY TRAJ
C
C  FIRST DETECT NON-ZERO START- THROW AWAY FIRST NONZERO NUMBER
C
      XL=0
100   X=XL
      CALL NIN(XL)
      IF (X.EQ. 0 ) GO TO 100
C
C  INITIALIZE,   XL = LAST X
C
      NCOIN=0
      NDEC=0
      NCHR=0
      NSUM=0
C
C  INPUT NUMBER STRING TO TRAJ ARRAY
C   LAST NONZERO LOST
C
200   CALL NIN(X)
      IF(NCHR.GE.400)GOTO 300
      XT=X-XL
      IF(XT.GT. 40) GOTO 300
      IF(XT.LT.-40) GOTO 300
      IF(X.EQ. 0) GO TO 300
      NCHR=NCHR+1
      IF (X.EQ. XL) NCOIN=NCOIN+1
      IF (X.LT. XL) NDEC=NDEC+1
      TRAJ(NCHR)=XL
      NSUM=NSUM+XL
      XL=X
      GO TO 200
300   NINC=NCHR-NCOIN-NDEC
      NSUM=(NSUM+NSUM+NCHR)/(NCHR+NCHR)
C
      RETURN
      END
```
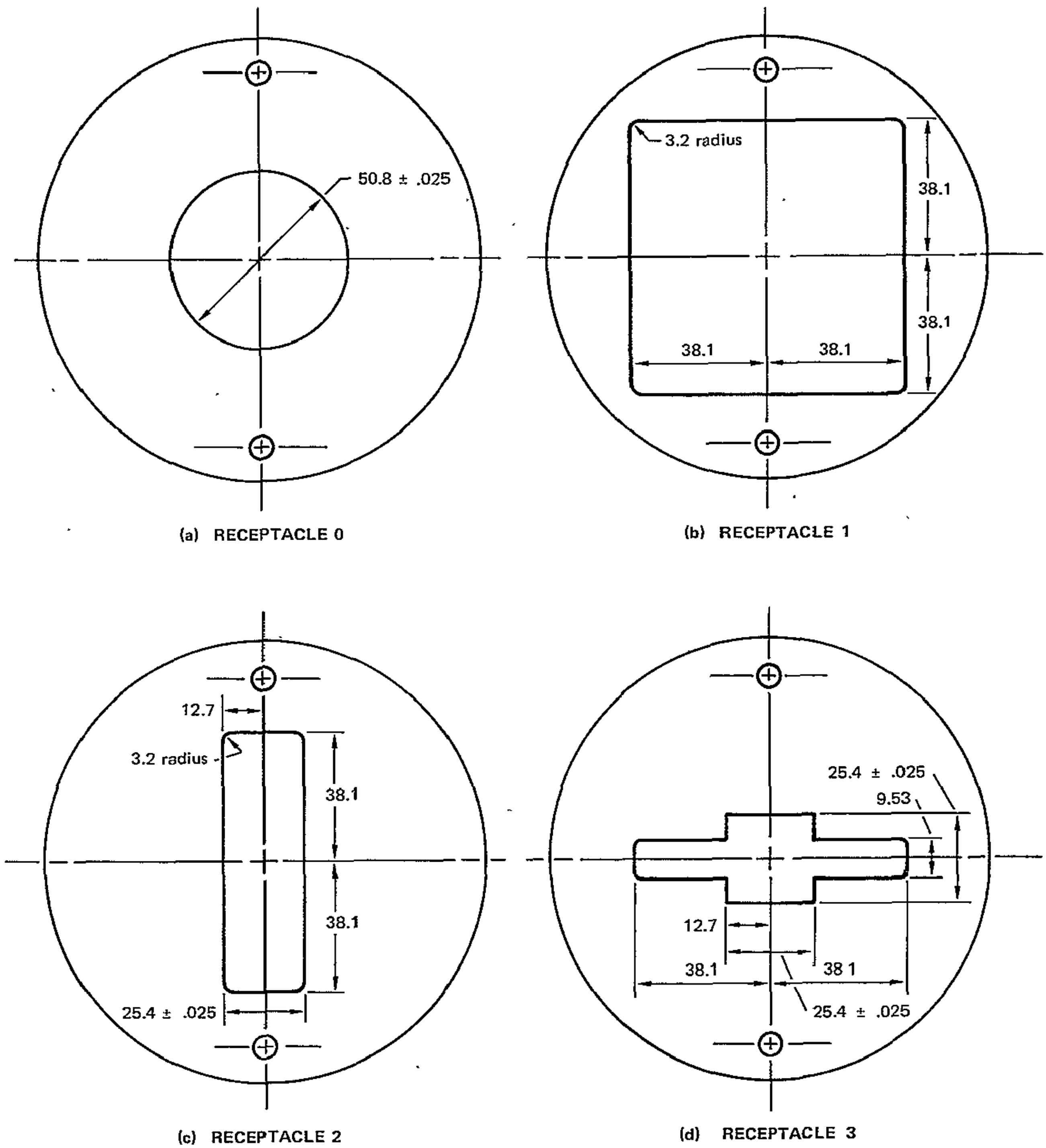

Appendix C

DIMENSIONS OF THE RECEPTACLES AND TOOLS



NOTE: All four receptacles are cut from 25.4 mm (1,000-inch) thick aluminum plate 127 mm (5 00 inches) in diameter.

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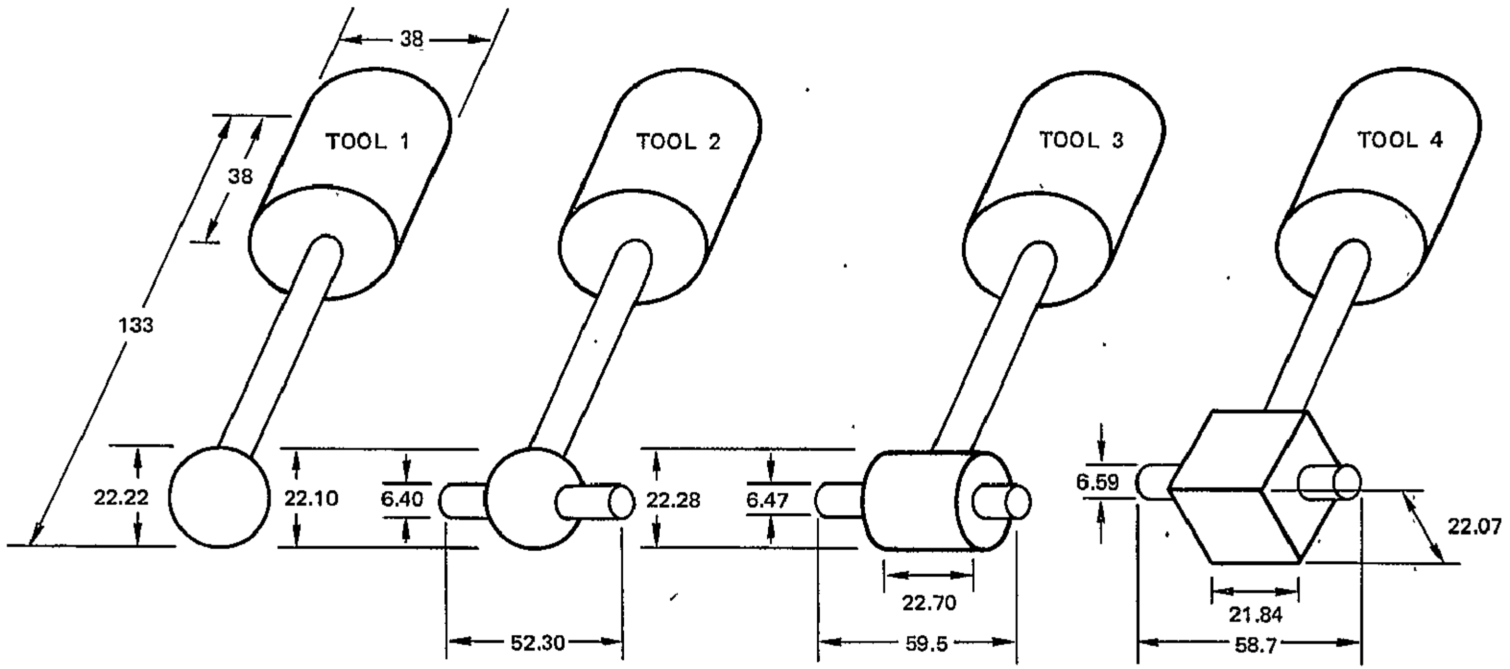
FIGURE C-1 DIMENSIONS OF THE FOUR RECEPTACLES



NOTE: Dimensions in millimeters.

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FIGURE C-2 DIMENSIONS OF THE FOUR TOOLS

PEG NUMBER	PEG DIAMETER (mm)
1	12.70
2	25.40
3	31.75
4	38.10
5	41.28
6	44.45
7	46.03
8	47.62
9	48.41
10	49.23
11	50.01
12	50.39
13	50.60
14	50.70
15	50.75

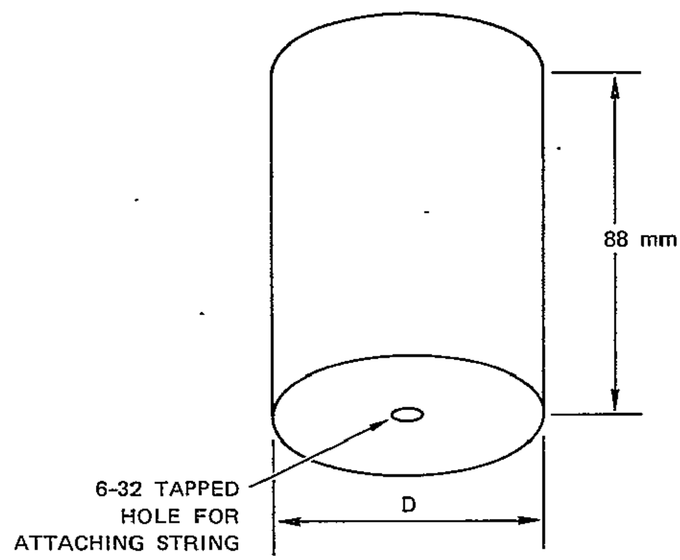

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FIGURE C-3 DIMENSIONS OF THE PEG SET

C-2

Appendix D

THE MA-11 MANIPULATOR*

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*The MA-11 data sheet prepared by the French Atomic Energy Commission (CEA) is reproduced as Figure D-1. Performance measurements (both joint-by-joint and overall) made by the CEA[6] are given in Tables D-1 and D-2.

The MA-11 is a light and highly sensitive 5 kg manipulator with motorised depth displacement. It can reach the ceiling of the hot-cell, and is designed for cells of 0.9 to 1.5 meters depth, with lead or cast iron shielding. It may be fitted exceptionally to concrete-shielded enclosures.

TYPICAL CELL OF USUAL DIMENSIONS

1 Manipulator
2 Window
3 Penetration and gamma shielding
4 Standard frame (140 mm in diameter)
5 Protecting booting
6 Tong
7 Tong exchange fixture.

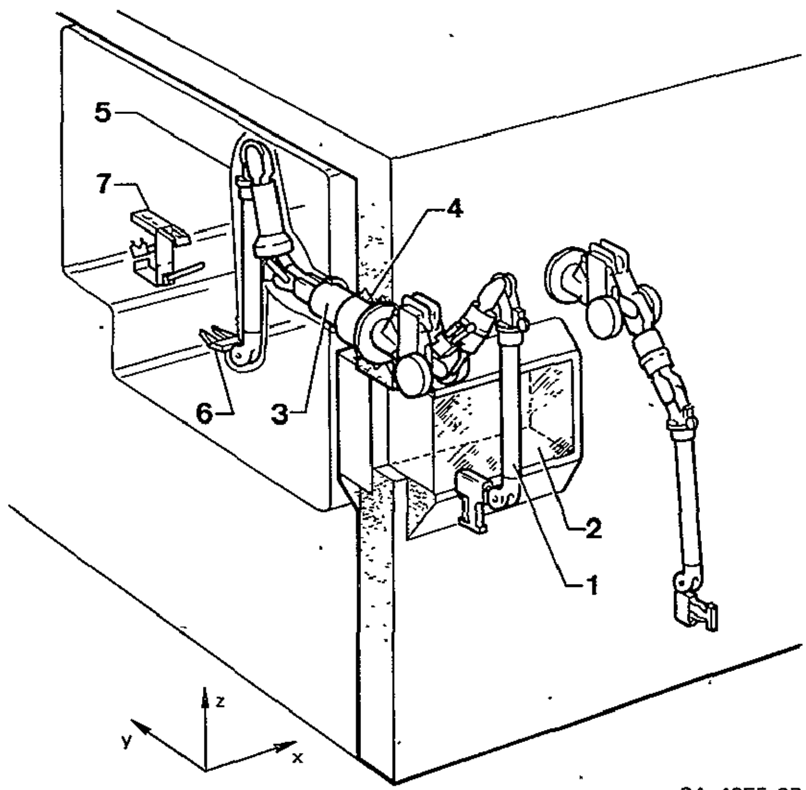

FIGURE D-1 DESCRIPTION OF MA-11

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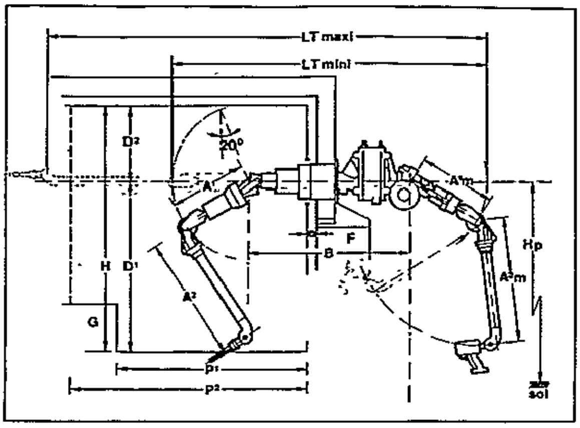


OBSERVATIONS

1/ Working level at 1 meter above floor.

2/ a is the distance between shielding and containment enclosure : generally 50 mm.

3/ Items not indicated in the drawing are :
L = width of work-post
E = between-centers of two manipulators.

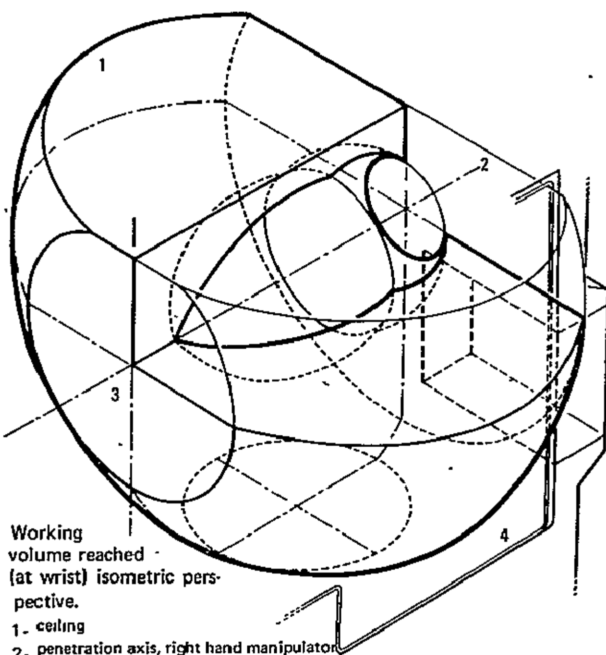
4/ G is a step provided for convenience.

5/ B varies with shielding thickness (5, 10 or 20 cm lead), the same applying to LT.

dimensions in mm.

DIMENSIONAL DATA

MANIPULATORS MA-11	OF CELL					OF SYSTEM				OF MANIPULATORS			
	P 1	P 2	step	L	H	D 1	D 2	Hp	E	A 1	A 2	A 1 m	A 2 m
normal range	1000	1250	250 x 250	1500	1300	900	400	1900	700	400	650	400	650
long range	1200	1500	300 x 300	2000	1400	900	500	1900	800	510	740	400	650



Working volume reached - (at wrist) isometric perspective.
1. ceiling
2. penetration axis, right hand manipulator
3. far wall
4. containment wall

COVERAGE

- The coverage is exceptionally extensive, particularly towards the top of the cell.

DESIGN :

Service Technique d'Etudes de Protection
Centre d'Etudes Nucléaires de SACLAY
BP n°2, 91 - GIF-SUR-YVETTE

MAKERS :

France : La Calhène
5, rue Emile Zola
95 - BEZONS
U.S A : Central Research Laboratories
Redwing (Minnesota).

C E.A. Licence

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FIGURE D-1 DESCRIPTION OF MA-11 (Concluded)

Table D-1

MA-11 PERFORMANCE JOINT BY JOINT

	Lateral X	Elbow Y	Shoulder Z	Forearm Rotation Azimuth	Wrist Tong Elevation	Wrist Tong Rotation
Inertia (kg)	2-5	1	6			
Friction (N)	3.1	0.8	3.5	0.6*	0.9†	1.2‡
Deflection (mm daN^{-1}) (Master to slave)	4.4	13.5	3.7	20	17	15
Full load (mm)	25	70	20	100	85	75
Backlash (mm)	8	8	0	0	10	2‡

*Limited by operator fatigue = 1 kg with one hand (3 kg with two hands)

†At tong tips

‡At one fingertip, tong opened at 80 mm.

Table D-2

MA-11 PERFORMANCE OVERALL

Mass capacity permanent	1-3 kg (limited by operator fatigue)
Mass capacity 60% duty cycle	5 kg any direction any position (movable by the indexing electric actuator)
Maximal force	8 kg against gravity
Rupture force	20 daN

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Appendix E

THE MA-23/200 MANIPULATOR

Appendix E

THE MA-23/200 MANIPULATOR

The manipulator MA-23 developed by the Atomic Energy Commission of France is servo-controlled. It has electronic control with a bilateral servomotor that has reverse power action, i.e., feel. Its dimensions appear in Figure E-1. The controls of the various movements are actuated by D.C.-coupled motors, and the mechanical movements are actuated by systems of stainless steel cables and tapes, thus eliminating backlash.

The manipulator is of the articulated type, resembling the human arm. The hand has only two fingers or tongs. The MA-23 allows an operator to easily carry out complex movements in rapid sequence. The load capacity is 200 N (41 lb) with a possible overload of 10 to 20%. Working volume is shown in Figure E-2.[7] The no-load response is within 0.5-1.0 m/sec for 1 to 4 g; with load, the performance is slightly slower. For manipulator type MA-23/200 N, arm weight is 180 kg. System performance for the three versions is given in Table E-1.[8] The 200 N, or heavy duty slave, was used in the experiments.

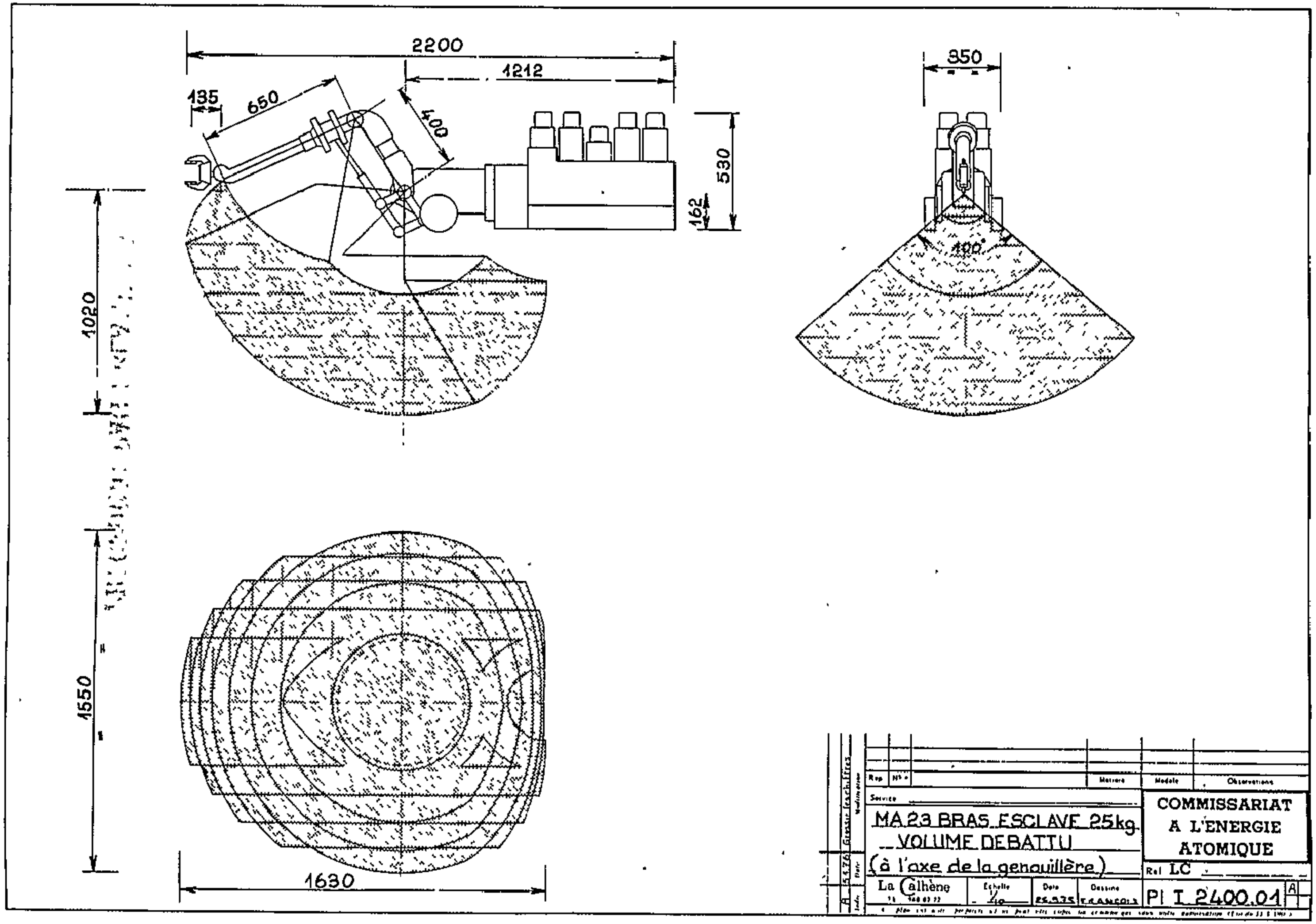

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FIGURE E-1 MA-23 SLAVE WORKING VOLUME (25 kg)

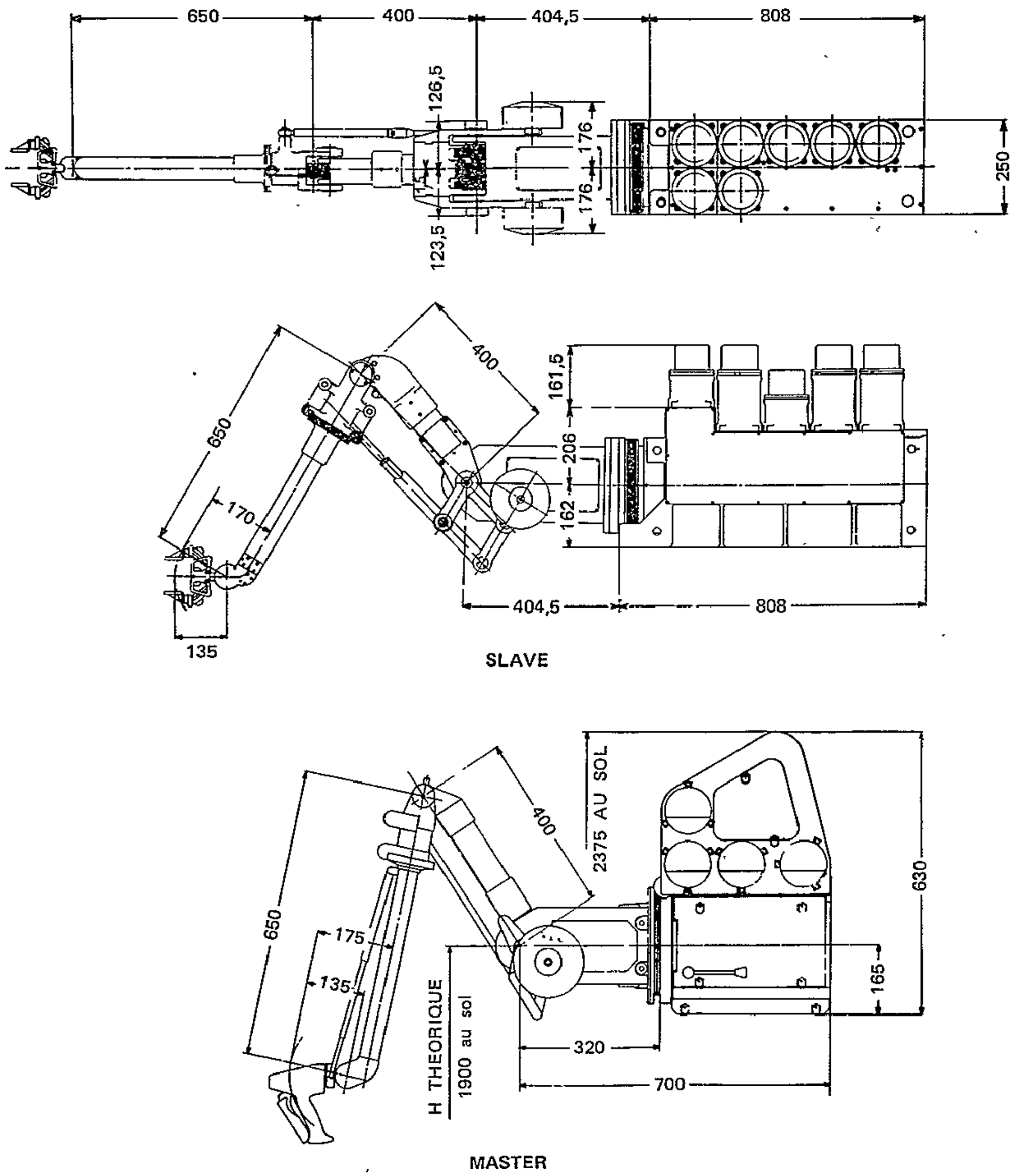

FIGURE E-2 DIMENSIONS OF THE MA-23 MASTER AND SLAVE

Table E-1

MA-23 SYSTEM PERFORMANCE

	Master Arm and Light Duty Slave	Standard MA-23/100	Heavy-Duty MA-23/200
	Force-Feedback Ratio		
	1/1 to 1/2	1/1 to 1/2	2/5 to 1/4
Mass capacity			
Maximal 20-30 minutes temporary load	6 kg	12 kg	24 kg (30)
Pay load 60% duty cycle	5 kg	10 kg	20 kg (25)
Permanent load 100% duty cycle	3.5 kg	7 kg	14 kg (17.5)
Maximal force			
Guaranteed in any direction, in any position	6 daN	12 daN	24 daN (30)
Inertia			
At arm terminal	2 to 5 kg	2 to 5 kg	5 to 12 kg
Reflected to master in master slave mode	3 to 7.5 kg	3 to 7.5 kg	3 to 7.5 kg
Acceleration			
With no load	Over 10 ms^{-2}	Over 20 ms^{-2}	Over 20 ms^{-2}
With pay load - horizontal	6 to 8.5 ms^{-2}	8 to 10 ms^{-2}	7 to 10 ms^{-2}
- vertical	1 ms^{-2}	1.3 ms^{-2}	1.3 ms^{-2}
Maximum velocity	Over 1.5 ms^{-1}	0.85 to 1 ms^{-1}	0.5 to 1 ms^{-1}
Friction			
At arm terminal - when off	1.5 to 3 N	2 to 6 N	5 to 10 N (6 to 12 N)
Reflected to master - when on	2 to 6 N	2 to 6 N	2 to 6 N
Deflection			
Arm alone	1 to 4 mm daN^{-1}	1 to 3 mm daN^{-1}	0.4 to 1.4 mm daN^{-1}
Full load master to slave	10 to 30 mm	14 to 56 mm	10 to 50 mm
Peak power	<500 watts	500 watts	1000 watts
Total mass (one arm)	90 kg	90 kg	180 kg

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