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EARTH ORBITAL TELEOPERATOR MANIPULATOR SYSTEM EVALUATION PROGRAM

TEST REPORT NUMBER 4

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FOREWORD

This 1976 year end Manipulator Laboratory Report is one of a set of three volumes that describe the teleoperator design studies performed by Essex Corporation under NASA contract NAS8-31848. The three volumes describe the tests conducted in the mobility, manipulator and visual laboratories at Marshall Space Flight Center (MSFC) and the concomitant results. This effort was directed by Mr. Edward G. Guerin (COR).

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1.0 EXECUTIVE SUMMARY

NASA's Marshall Space Flight Center (MSFC) is currently involved in the development of technology to support teleoperator flight experiments. Development and evaluation is being performed in three technology areas:

- Visual Systems
- Manipulator Systems
- Vehicle Mobility Systems

The current report describes two series of tests performed to assess the operator's ability to perform five manipulator tip movements while using monoptic and stereoptic video systems. Test data obtained were compared with previous results to determine the impact of camera placement and stereoptic viewing on manipulator system performance.

The tests were performed using the NASA MSFC Extendible Stiff Arm Manipulator (ESAM) and an analog joystick controller. All tests were conducted at the MSFC Manipulator System Evaluation Laboratory. Two basic manipulator tasks were utilized. The minimum position change test required the operator to move the manipulator arm to touch a target contact. The dexterity test required removal and replacement of pegs.

1.1 MINIMUM POSITION CHANGE TEST

This task was carried out by test subjects under several conditions of movement amplitude, terminal accuracy and target orientation. Two different stereo camera pair positions were used:

- Camera pair normal to task board and parallel to manipulator longitudinal axis
- Camera pair offset to right and panned to view task board at 45° angle.

Performance was assessed by means of response time and target contact errors. Response time was found to be significantly influenced by all independent variables except camera orientation. This result verifies an important effect of stereoptic viewing. With stereoptic video, depth cues can be obtained over a range of camera positions. With monoptic TV, availability of critical depth cues is strongly dependent on camera position.

1.2 DEXTERITY TEST

The dexterity test required the subject to achieve more precise manipulator tip orientation than did the minimum position change test. The dexterity test required removal and replacement of pegs of various diameters. The stereo TV system was used in two modes:

- Camera pair normal to task board and parallel to manipulator longitudinal axis
- Camera pair mounted on the manipulator.

Performance was measured by the time from task initiation to peg removal and by peg transfer time. Both variables were influenced by peg size. The effect of camera location was not found to be satistically significant.

1.3 COMPARISON OF STEREOPTIC AND MONOPTIC VIDEO SYSTEMS

Statistical comparisons were carried out in which mean response times for the minimum position change and dexterity tests under stereoptic viewing conditions were contrasted with corresponding data using a two-channel monoptic system. The introduction of stereo viewing resulted in a reduction of mean response time from 11.39 to 6.39 seconds for the minimum position change test. In the case of the dexterity test, the corresponding change was a reduction in transfer time from 40.35 to 22.95 seconds. The current data thus show a considerable effect of changing from a monoptic to a stereoptic video system for remote manipulation tasks.

2.0 INTRODUCTION

2.1 BACKGROUND

NASA's Marshall Space Flight Center is currently involved in the development of technology to support two teleoperator flight experiments - the Space Teleoperator Demonstration Unit (STDU) and the Space Teleoperator Evaluation Vehicle (STEV). As currently conceived, the STDU will be mounted in the Shuttle payload bay where it will perform a variety of simulated payload servicing tasks to evaluate the manipulator and visual systems. The STEV will be a fully mobile teleoperator system complete with propulsion and attitude control systems.

The initial tests of teleoperator technology will be performed using the STDU on an early Shuttle flight. Since the STDU will operate in the payload bay, a vehicle mobility system will not be required. The other system components including the manipulator arm, end effector, visual system, data links, controls, displays and control laws will be required, however.

NASA's long-range teleoperator goals include development of a fully functional STEV with operating propulsion and stabilization systems. The STEV will be released from the Shuttle to demonstrate its maneuvering, inspection and servicing capabilities.

Several major technology questions must be answered before the STDU and STEV can be developed. The MSFC teleoperator development effort is aimed at the three primary technology areas - the visual system, the manipulator system, and the maneuvering/mobility system. In each area, a central problem is the definition of requirements and criteria for the man-machine interface. The testing philosophy being employed is to use simulation and laboratory testing to evaluate man-machine interface concepts and develop a system/

operator data base. These data will then be used to specify man-machine interface requirements for the three technology areas. This approach has led to the establishment of laboratory facilities for visual system integration and evaluation, manipulator system and control concept testing, and mobility system evaluation.

Essex Corporation is currently under contract to NASA/MSFC to perform laboratory tests of system/operator performance, to evaluate man-machine interface concepts, and to derive man-machine interface requirements. Essex personnel have defined manipulator, visual and mobility system tasks typical of those to be encountered by the STDU and STEV and have developed laboratory and simulation test plans based on these tasks. These test plans have been implemented and carried out in the various MSFC laboratories resulting in quantitative performance data suitable to support trade-off studies of system concepts and choice of system parameters. Essex has also carried out a variety of analytical studies in the area of man-machine interface requirements.

2.2 SCOPE

In this 1976 year end report, the specific activities performed in the Manipulator System Evaluation Laboratory are described, along with facility and manipulator systems. During the year, two series of tests were conducted to (1) evaluate an operator's ability to perform fine manipulator tip movements while using a remote hand controller and TV display, and (2) determine an operator's capability to grasp, control and fine position various size objects using a six degree-of-freedom manipulator, a remote hand controller and a stereoptic TV system. Manipulator tests reported previously have employed a video system consisting of two orthogonal monoptic cameras. A variety of controller types were compared for the ESAM and RAM manipulators. In the tests currently being reported, the effect of changing to a stereoptic video system with a fixed manipulator/controller system was determined.

3.0 MANIPULATOR AND CONTROLLER DESCRIPTIONS

The development of remote manipulation systems applicable to Shuttle missions is being preceded by a series of comprehensive investigations into existing remote manipulator technology, and operator control and management of remote manipulator systems. NASA's RMS/EVA committee has assigned to MSFC the responsibility for teleoperator technology development and integration, especially as it applies to the two currently conceived teleoperator systems - the Space Teleoperator Demonstration Unit (STDU) and Space Teleoperator Evaluation Vehicle (STEV).

As part of its overall effort, MSFC developed the Teleoperator Technology Development Plan and in the implementation of this plan, established the Manipulator System Evaluation Program. MSFC's Electronics and Control Laboratory houses the Manipulator System Evaluation Laboratory (MSEL) which has been the focal point for gathering experimentally derived data on existing manipulator systems applicable to space missions. The MSEL provides the necessary controlled environment for the study of each of the components of the manipulator system and the interactions of the several manipulator system components. As is the case in each of the other major teleoperator subsystems, the evaluations of manipulator systems represent only part of a more extensive effort to adequately define the effects of system parameters, mission requirements, task conditions, human operator performance, and state-of-the-art equipment designs which may impact the use of remote manipulators on Shuttle missions.

The strategy for the conduct of manipulator system investigations is described in the "Remote Manipulator System Evaluation Criteria" (Reference 1, Section 2.1).

This final report describes the performance results of a basic manipulator system tested on the minimum position change and dexterity task modules. The manipulator system tested and described herein is the Extendible Stiff Arm Manipulator (ESAM).

3.1 ESAM MANIPULATOR

The ESAM is a modular non-anthropomorphic, six degree-of-freedom (DOF) manipulator (seven if grasp is defined as a DOF) representing the state-of-the-art achievement for general purpose remote manipulator units. The ESAM was designed and developed at MSFC and evaluated at the Manipulator System Evaluation Laboratory.

The ESAM, shown in Figure 3-1, is basically a tubular, fixed member having a square cross section which provides support and storage for an extendible/retractable stiff member. The extendible member has a wrist assembly which provides roll, pitch and yaw positioning for the end effector. The manipulator arm azimuth and elevation position motors and the extend/retract motor are mounted to the fixed member. Each ESAM joint is driven by a 28 vdc reversible motor through a planetary gear system to a harmonic drive transmission. These operating characteristics are given in Table 3-1.

ESAM operation entails azimuth/elevation at the shoulder joint. The entire outer and inner member and wrist assembly may be moved through an azimuth angle via a 28 vdc motor acting through the planetary gear system. The elevation motor and drive assembly is inside the azimuth assembly. The two joints and associated driving assemblies can move the fixed member in a 360 degree envelope in azimuth and 180 degrees in elevation.

The extendible member is a square cross sectional tube which telescopes from

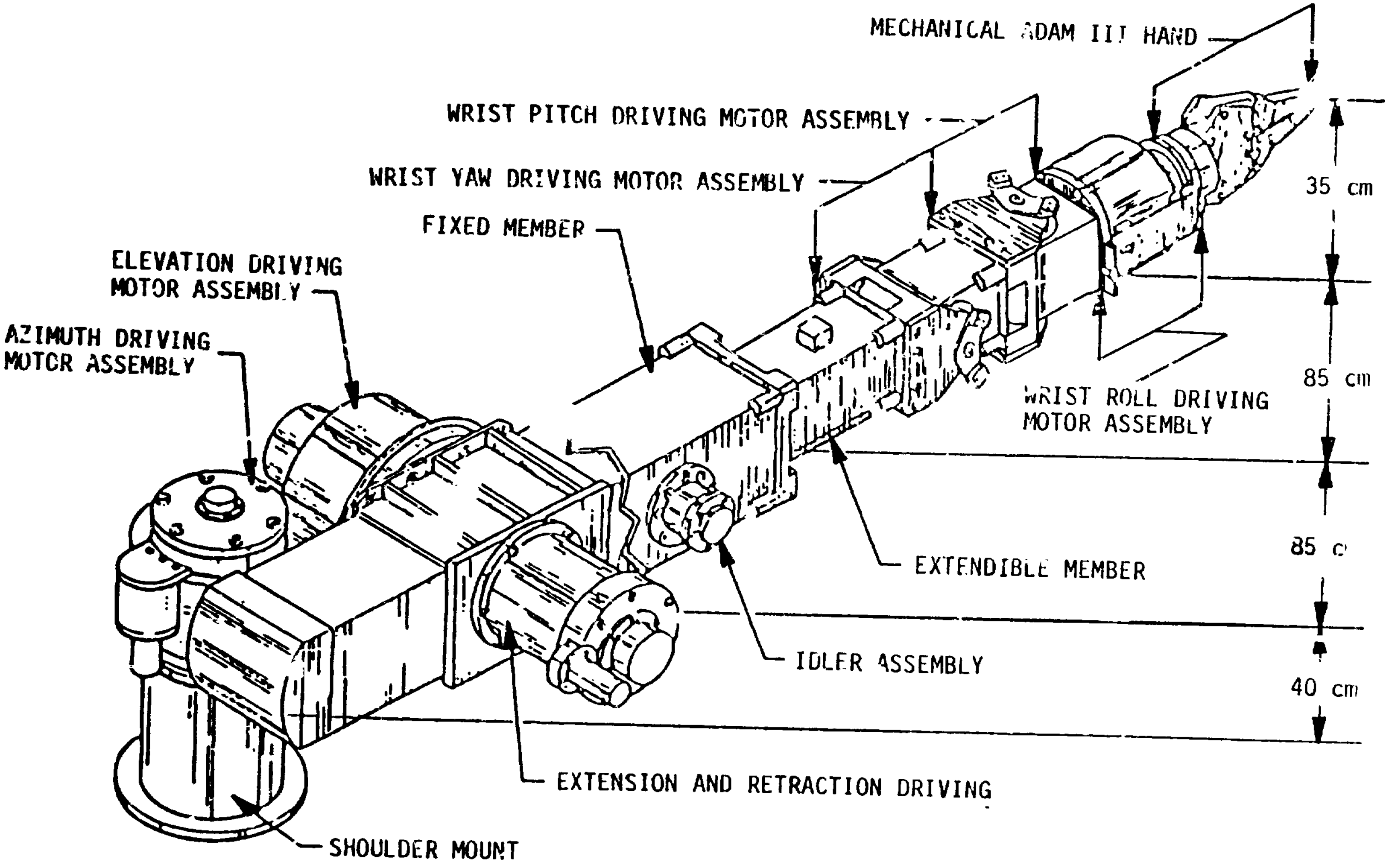

Figure 3-1: Six Degree-of-Freedom Stiff Arm Manipulator System (ESAM)

Table 3-1: ESAM OPERATING CHARACTERISTICS

	Max. Possible Displacement	Rate (Max)	Motor Drive	Gear Ratio
ARM/SHOULDER				
Azimuth	660°	27° sec	12.5 Kg-M	480:1
Elevation	180°	16° sec	12.5 Kg-M	800:1
Extend/Retract	68 cm. (27 in.)	9.1 cm sec (3.5 in. sec)	4.1 Kg-M (40 oz-in.)	120:1
ARM/WRIST				
Roll	540°	30° sec	1.6 Kg-M	480:1
Pitch	120°	14° sec	1.6 Kg-M	480:1
Yaw	120°	14° sec	1.6 Kg-M (15 oz-in.)	480:1
Jaw	7.6 cm (3.0 in.)	62° sec	5.7 Kg-M (55 oz-in.)	

within the fixed member. The extension member is driven by a 28 vdc drive system. The extension range is 68 cm (26.75 in.). The end effector assembly also uses 28 vdc motors to drive the effector through 120 degrees in pitch and yaw and 540 degrees in roll.

3.2 ANALOG JOYSTICK CONTROLLER WITH RESOLVED RATE CONTROL

This controller concept is an analog joystick in which there is a geometric correspondence between the operator's controlling movement and the manipulator resulting motion. The analog joystick controller was designed and fabricated by Rancho Los Amigos Hospital, Inc. for the MSFC Manipulator Laboratory. The controller, shown in Figures 3-2 and 3-3, combines the attributes of a position translation control system and a rate attitude control system.

The control system consists of the drive linkage, control handle or joystick, and the position and rate control electronics. The drive linkage constitutes a mechanical analog resolver which converts Cartesian joystick coordinates into the polar coordinate system which best describes the azimuth, elevation and extension degrees-of-freedom of the manipulator arm. A point within the wrist mechanism may be considered as a controlled element having X, Y and Z coordinates with the two elements linearly related to produce wrist position as a linear function of controller position. The correspondence, however, is effected by azimuth, elevation and extension degrees of freedom so that controller X, Y and Z commands cannot directly be input to the arm motors. A transformation of coordinates is required to resolve the Cartesian system command voltages into the polar system coordinates suitable as motor commands.

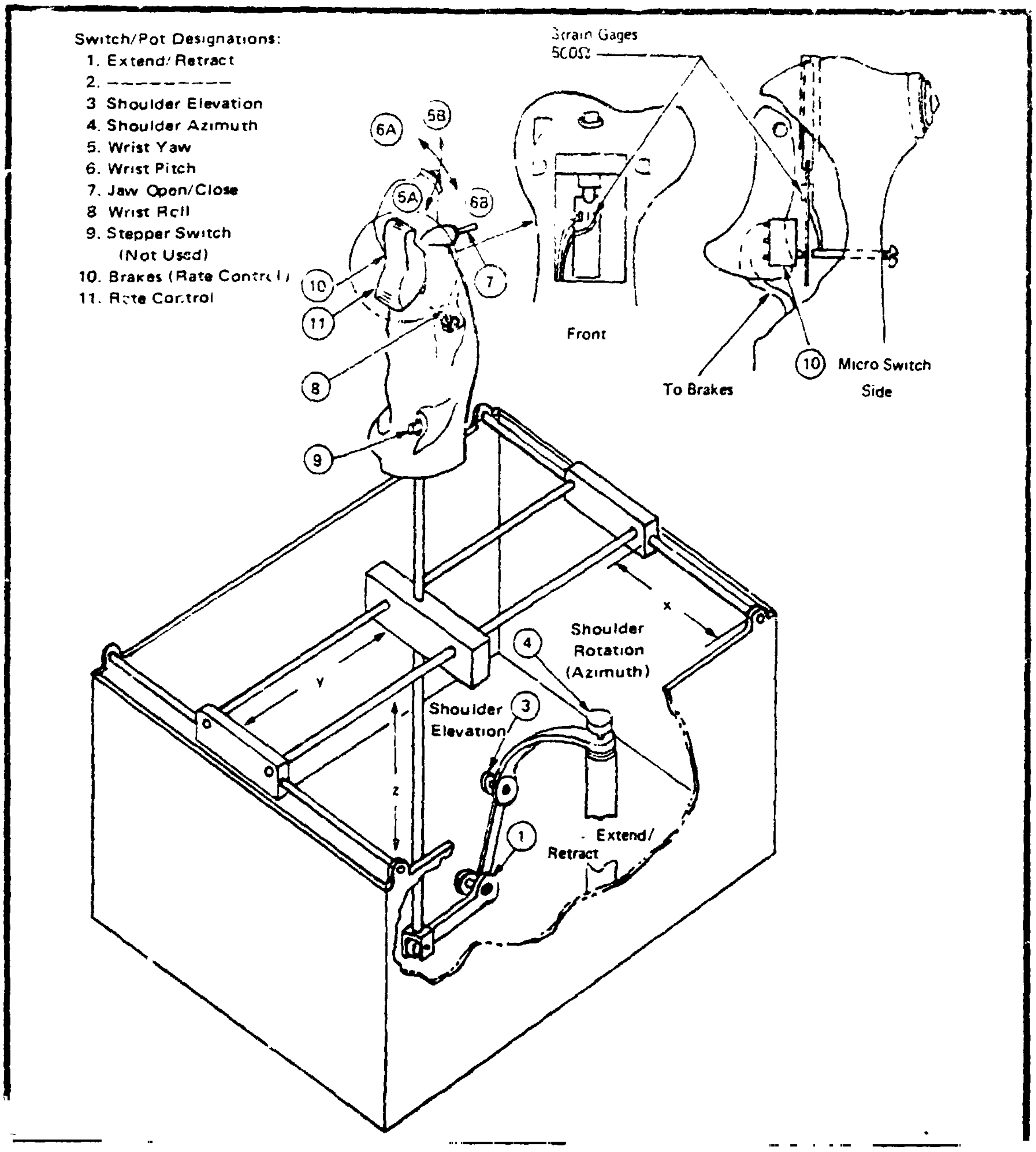

Figure 3-2: The Analog Joystick Controller Depicting Switch Functions for the 6 DOF ESAM Dexterity Test

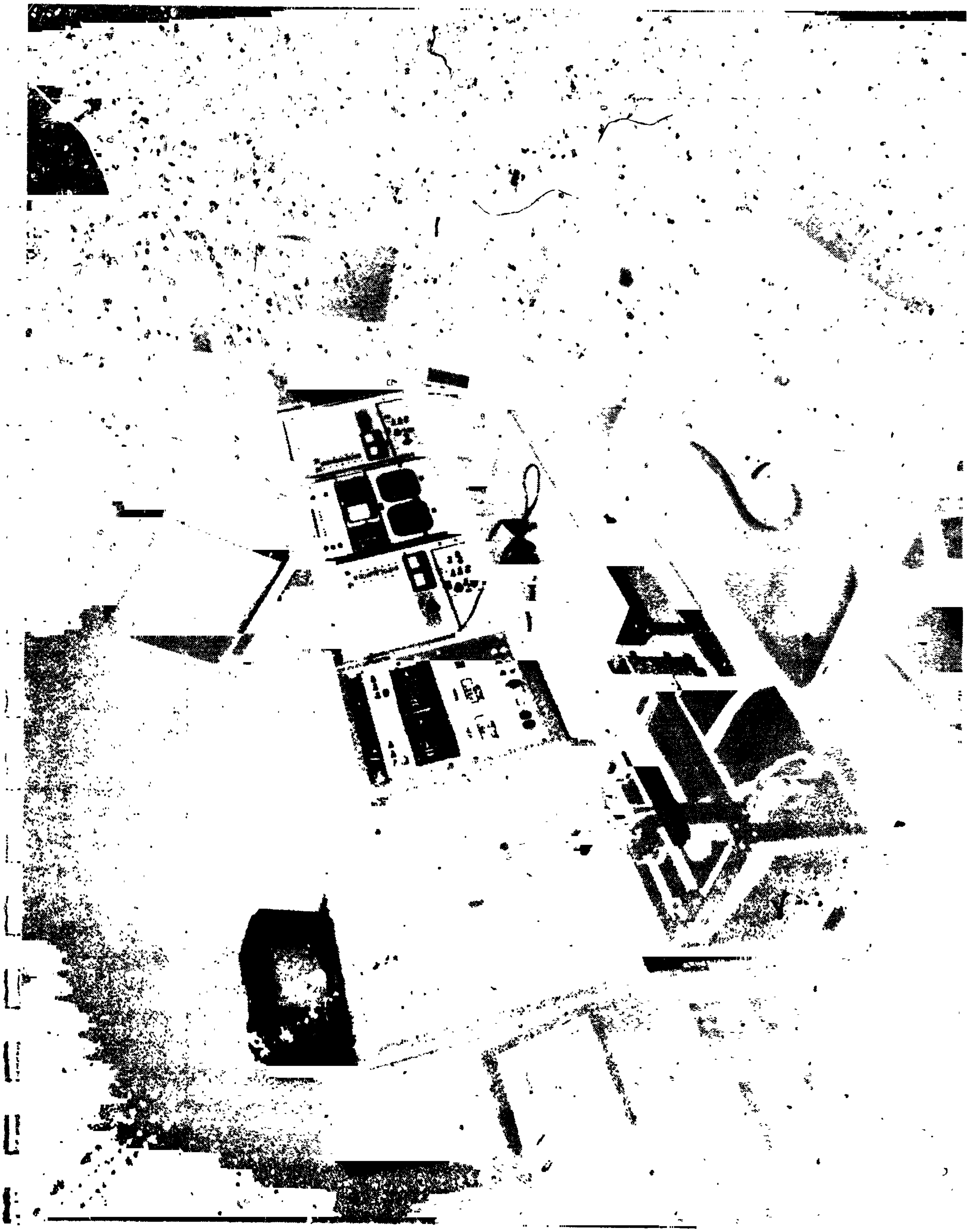

Figure 3-3: Operator's Station with Analog Controller and Stereo Set-up

The four bar linkage resolves the movements of the controller into pure translation actions which are converted into azimuth, elevation and extension position values by a rack and pinion and rotary potentiometers.

Two control modes are used for the position and rate control systems. The analog joystick controller employs a position command system with appropriate dead bands for azimuth, elevation and extension to yield accurate positioning of the end effector. A potentiometer in each drive linkage joint generates the command signal to drive the corresponding joint on the manipulator. This is accomplished by moving the hand controller which changes the drive linkage system reference position creating an error signal. The manipulator motor for the joint involved is driven at its maximum rate in the appropriate direction to decrease the error to the error signal threshold. When the error is within the deadband, the manipulator motor is then operated in a pulsed mode into the final deadband and movement stops (i.e., the position is matched) until a new error signal is supplied by changing the position of the control potentiometer. The end effector joints (roll, pitch and yaw, and grasp) are rate commanded and controlled. Direction is selected using appropriate switches (see Figure 3-2) on the handle, and rate is controlled by the amount of pressure applied to the trigger mounted to the joystick. Releasing the trigger dynamically brakes the drive motor.

4.0 MANIPULATOR SYSTEM EVALUATION LABORATORY CONFIGURATION

The MSFC Manipulator System Evaluation Laboratory (MSEL) is a general purpose facility providing the laboratory space and hardware necessary to collect quantitative data on manipulator system performance. The primary elements of the laboratory include:

- A manipulator system with associated controller(s), electronic control subsystem and visual subsystem.
- A task board placed suitably within the manipulator system's reach envelope.
- A remote operator's station providing all controls and displays necessary to operate the manipulator system and visual subsystem.
- An experimenter's station providing the controls necessary to conduct the tests and the displays necessary to record system performance data.

4.1 FACILITY DESCRIPTION

Two rooms are used to perform the manipulator tests - the manipulator room and the control room. The two rooms are shown in Figures 4-1 through 4-3.

The manipulator room contains the ESAM along with its support equipment including lights, cameras and task board. The experimenter is stationed near the manipulator so direct visual observations concerning operation of the arm can be made. The task board is positioned in the room and conditions of environmental control (light level) are established. The control room contains the operator's station which has the analog joystick controller placed between the operator and the stereo video monitors. The operator is located in the control room where communications between the experimenter and operator

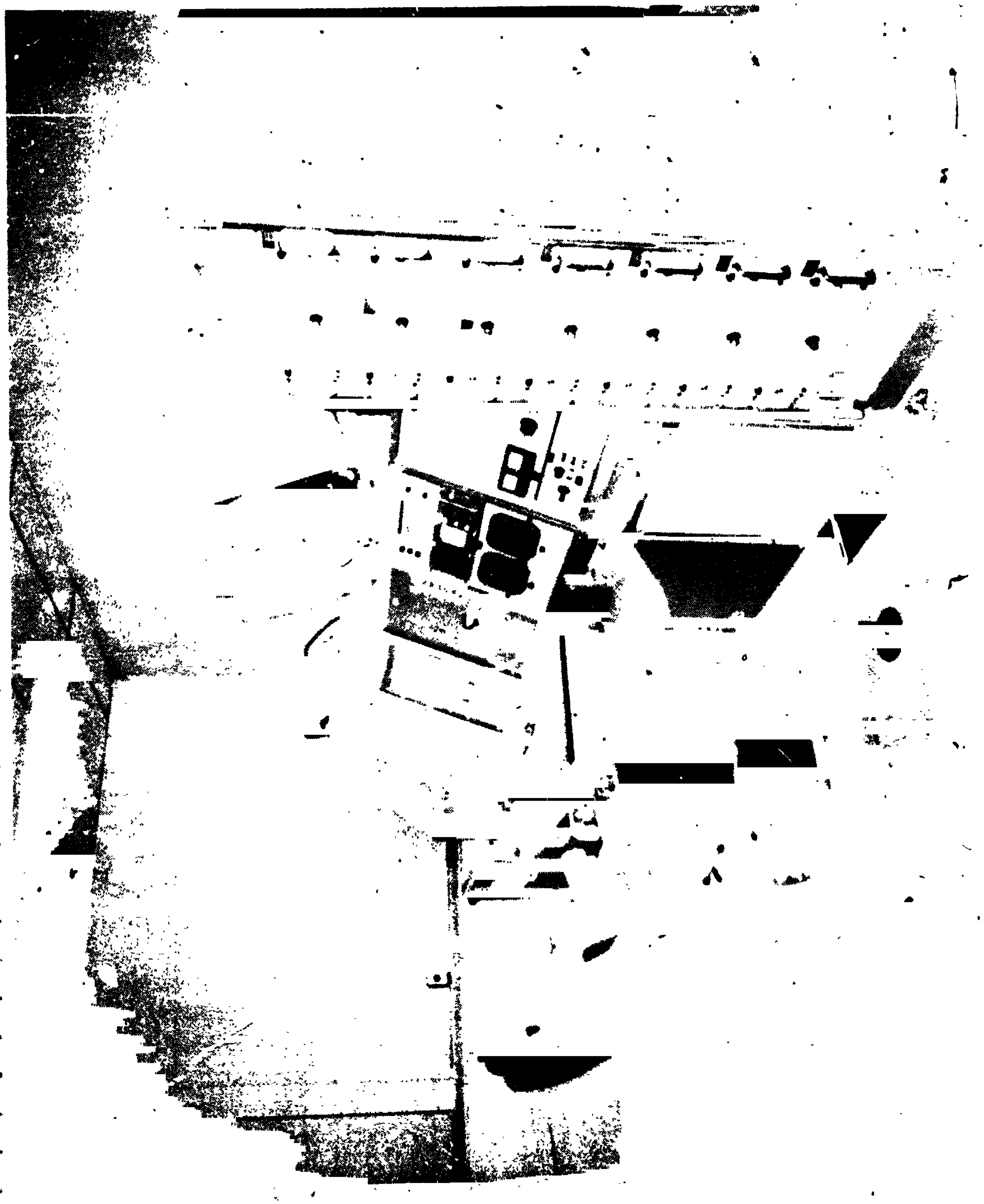

Figure 4-1: Control Room

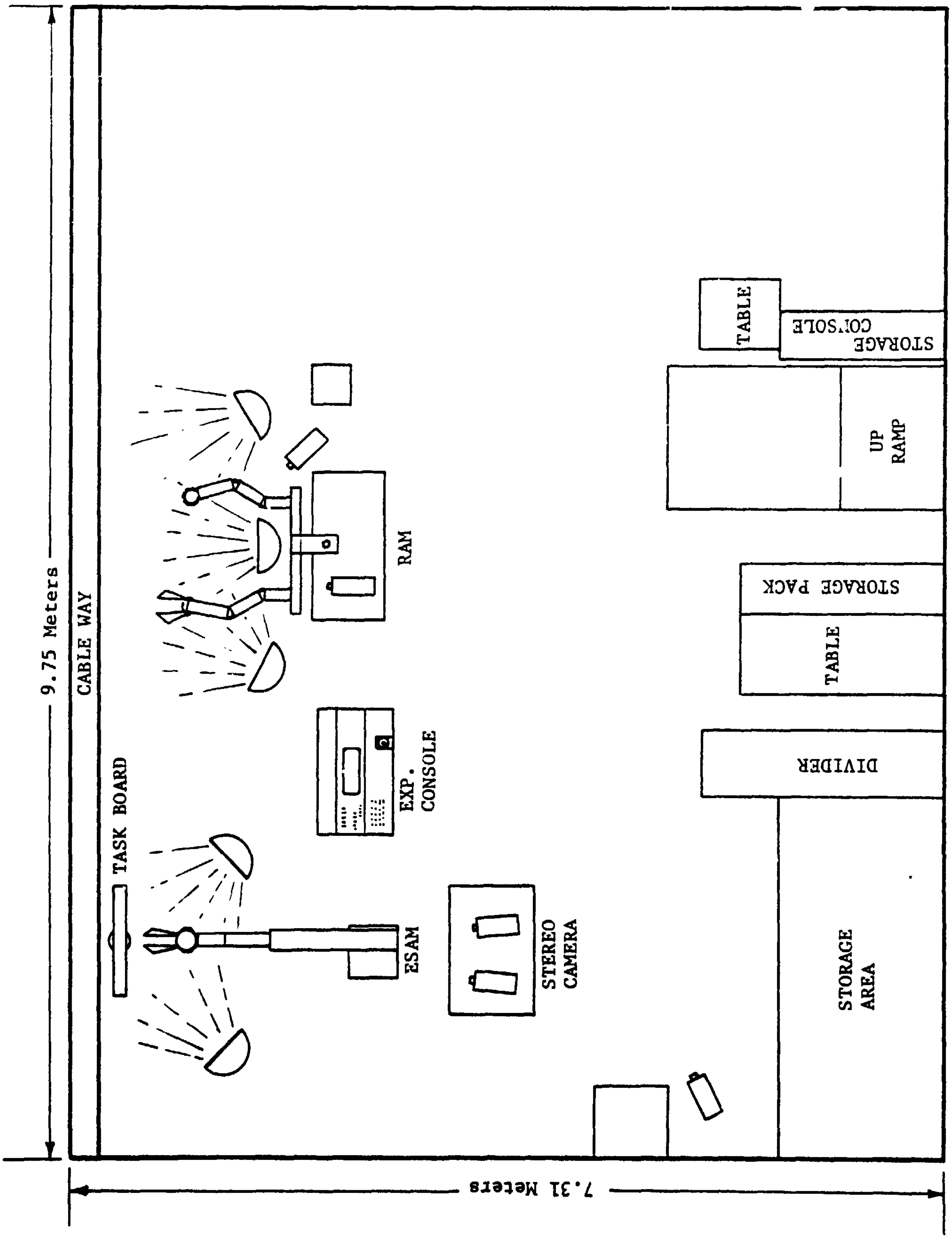

Figure 4-2: Manipulator Room

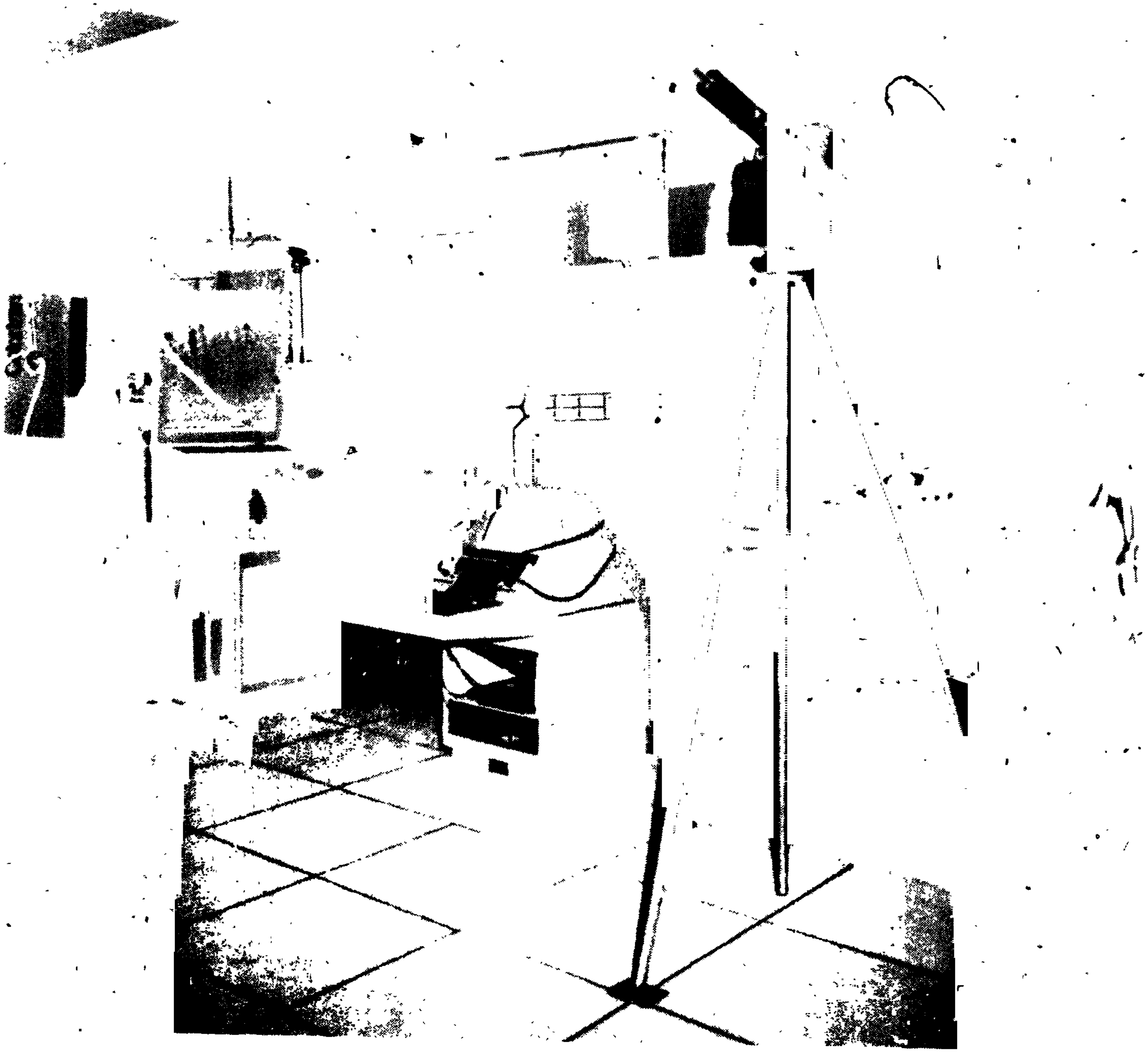

Figure 4-3: Manipulator Room Showing ESAM and Experimenter's Test Console

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are maintained via headsets which also minimizes audio feedback from the manipulator operations.

4.2 STEREOPTIC VIDEO SYSTEM

The video system and associated equipment used throughout the testing program consist of the subsystems described below and in Reference 5.

The operator's station contains the Fresnell stereoptic display. The display is mounted in a console containing the two 23 cm (9 in., diagonally measured) Conrac monitors and the associated optical train composed of mirrors and lenses as described in Essex Report H-77-3. The Fresnell display viewed by the subject is a single 23 cm (9 in.) screen. Ambient lighting is provided by a diffused overhead flourescent lamp set at 8.6 lumens/sq. meter as measured at the analog controller with a Tektronix Model J16 digital photometer.

The video system consists of a pair of COHU cameras, each mounted on a base plate which allows independent movement of the rear of the camera body about a vertical fulcrum located beneath the front of the vidicon tube face as shown in Figure 4-4. The distance between these two fulcrums (camera baseline) is 12.7 cm (5.0 in.). The iris, zoom and focus functions are preset for the testing program and their levels are verified between test runs.

All ranges and convergence point distances are measured from a point equidistant from each fulcrum along the baseline of the stereo camera pair.

The stereo camera video system consists of the following individual components:

- Two TV cameras, COHU Model 2006-011
- Two telephoto zoom lens, Canon Camera Company, Inc., Model TV 10 x 15, 16.5-95 mm, 1:2
- One tripod, Hercules, Inc., Model 5454, for camera height adjustment

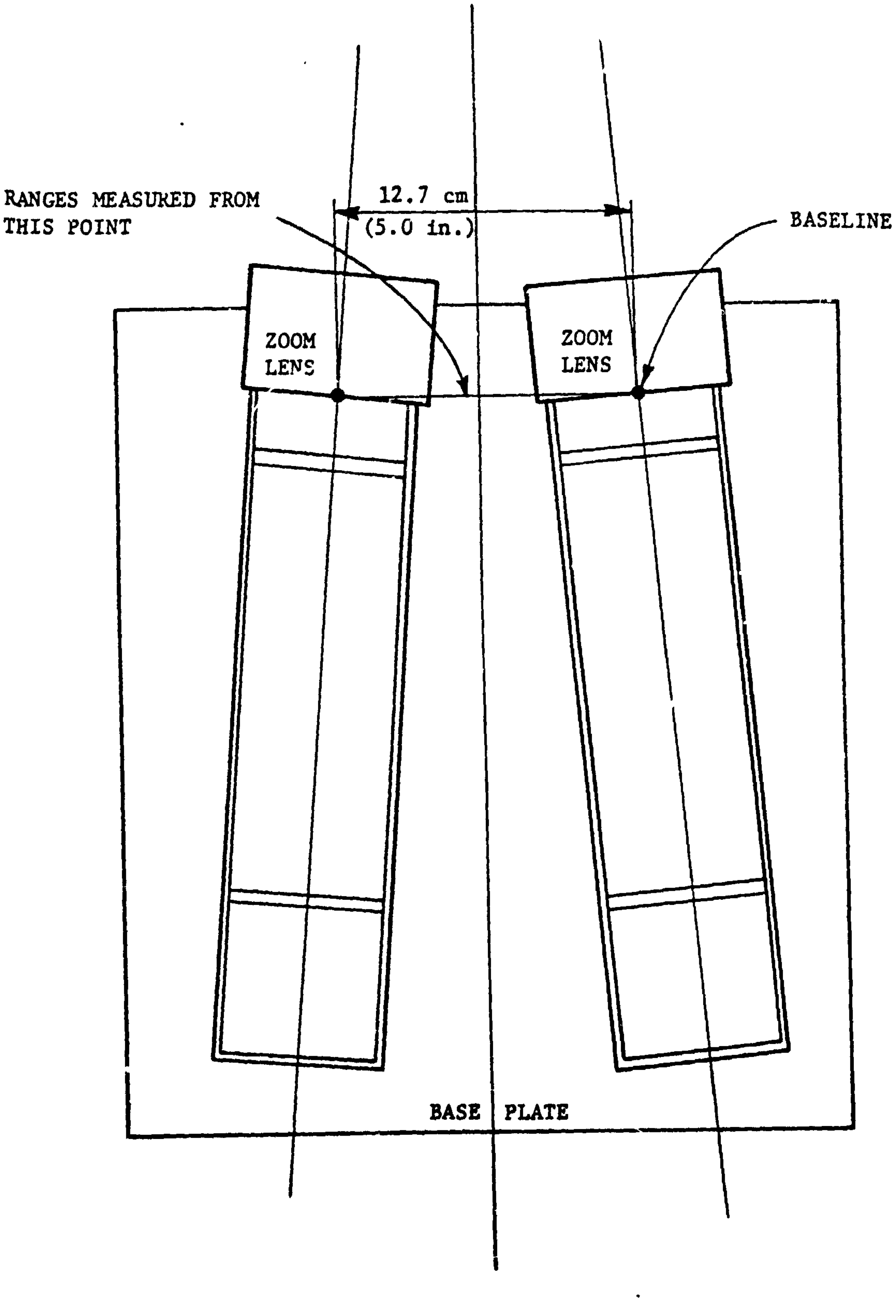


Figure 4-4: Stereo Camera Setup for Minimum Position Change Test

- Two camera remote control panels, COHU Electronics, Inc.

Each video system generates a 525 line analog signal at 4.5 MHz at the Conrac monitors. The signal to noise ratio is 32 dB.

5.0 MINIMUM POSITION CHANGE TEST APPARATUS, EXPERIMENTAL DESIGN, AND GENERAL TEST PROCEDURE

5.1 TEST OBJECTIVES AND APPARATUS

The minimum position change test was designed to determine the time required for a subject using a manipulator system to complete a fine movement of the manipulator tip requiring a fixed amplitude and terminal accuracy. The task utilized a flat, black phenolic task board which had a center contact and sixteen circular target contacts representing four levels of tip movement amplitude and four levels of tolerance (contact diameter). The task board was mounted normal to the X-axis of the manipulator system and had a mean range of 25 cm (10 in.) from the end effector tip at the start of each test run. The dimensions of the task board and cruciform arrangement of targets are shown in Figure 5-1.

A stylus was constructed using a 2.54 cm square phenolic base in which was mounted a spring loaded aluminum probe extending 2.54 cm beyond the phenolic base. The probe was 5 mm (0.2 in.) in diameter with a beveled tip. A 12 vdc power source was employed to close a circuit through the stylus and target contact. The circuit included a set of relays and switches to start an electronic timer when contact was made by the stylus at the center disc, and to stop it when the designated target contact was touched by the stylus, thereby yielding a measure of movement time.

5.2 EXPERIMENTAL DESIGN

During the test, three target parameters were varied to determine the effect on task times and tip placement accuracy. These independent variables were:

TARGET		DIAMETER
1	○	7 mm
2	○	10 mm
3	○	13 mm
4	○	16 mm

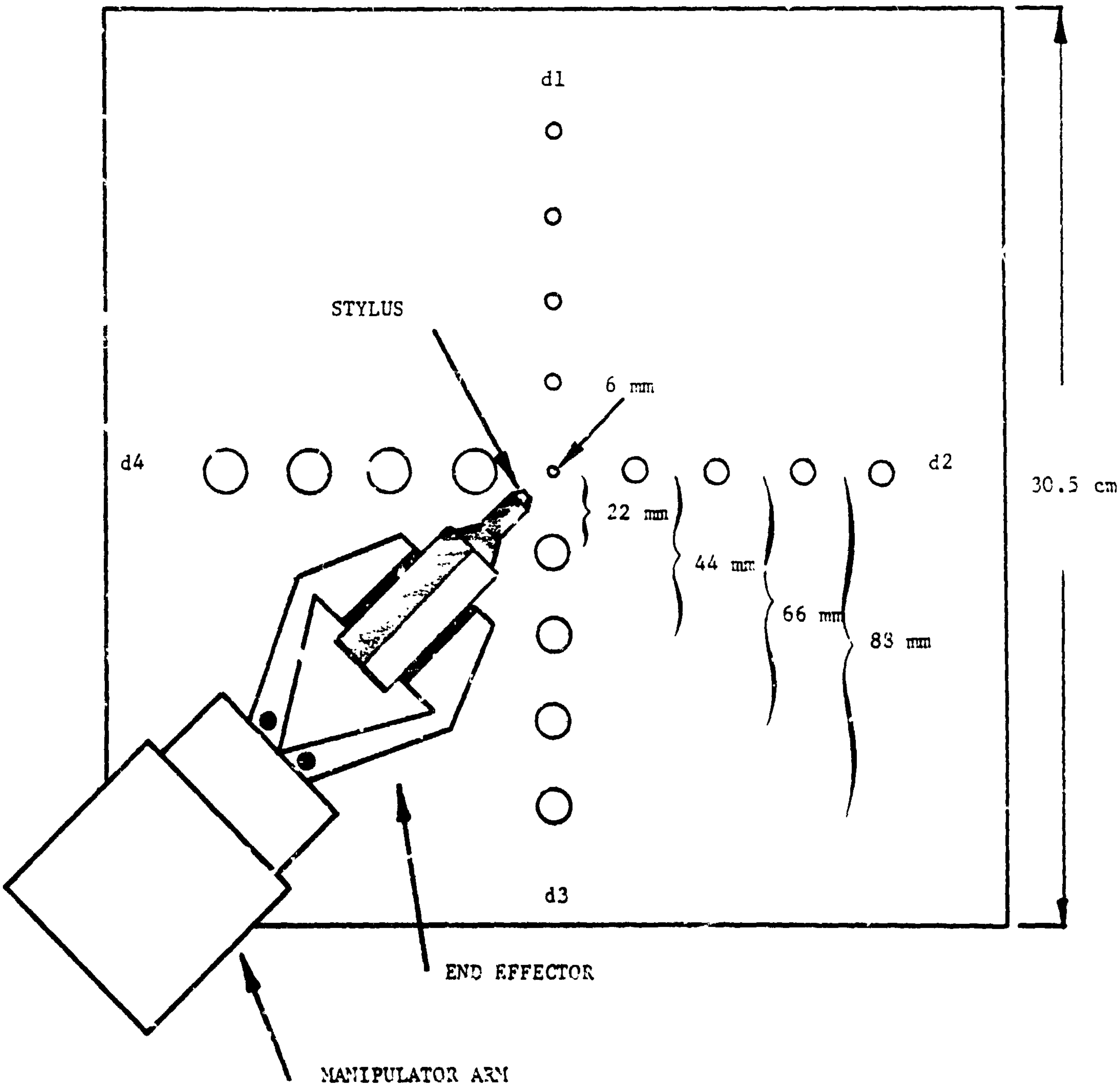


FIGURE 5-1: TASK MODULE FOR MINIMUM POSITION CHANGE TEST
(NOT DRAWN TO SCALE)

- Four target contact sizes (diameter)

  1) 0.7 cm
  2) 1.0 cm
  3) 1.3 cm
  4) 1.6 cm.

- Four conditions of target separation from the center contact (center to center distance)

  1) 2.2 cm
  2) 4.4 cm
  3) 6.6 cm
  4) 9.0 cm.

- Task board rotation orientation

  The task board was adjustable from 0° to 360°. Board orientations are described under each test section.

- TV camera locations

  1) Camera 1 - boresighted with the center of the task board and 0° with respect to longitudinal axis of ESAM
  2) Camera 2 - offset at 45° to the right with respect to longitudinal axis of ESAM and task board.

- TV camera geometry

  1) Camera 1 - 0° offset
     Range = 239.8 cm (94.4 in.)
     Baseline = 12.7 cm (5.0 in.)
     Target = 7.6 cm (3.0 in.)
     Image = 2.5 cm (1.0 in.)
     Convergence = 200.3 cm (78.8 in.)
     K (Field of View) = IR/T = 80 cm (31.5 in.)
     D (Disparity) = BK/C - BK/R = .8 cm (0.32 in.)
     camera base plate pitch down angle = 5°
     camera height = 161.5 cm (63.5 in.)
     task board height (CG to ground) = 130 cm (51.2 in.)

  2) Camera 2 - 45° offset
     Range = 274.3 cm (108 in.)
     Baseline = 12.7 cm (5.0 in.)
     Target = 7.6 cm (3.0 in.)
     Image = 2.5 cm (1.0 in.)
     Convergence = 165.1 cm (65 in.)
     K (Field of View) = IR/T = 91.4 cm (36 in.)
     D (Disparity) = BK/C - BK/R = 2.8 cm (1.1 in.)
     camera base plate pitch angle = 0°
     camera height = 130 cm (51.2 in.)
     task board height = 130 cm (51.2 in.).

The control variables were;

- TV signal parameters
  1) analog signal format - 4.5 MHz
  2) 32 db S/N ratio
- Lighting level at task board
  1) three banks of flourescent lamps which produced 1076 lumens/sq. meter.

The dependent measures recorded during each test were:

- Initial condition (IC) to center contact: Elapsed time to move from IC position to center contact
- Response time: Elapsed time to complete positional change from center contact to designated target
- Errors: Accuracy of commanded positional change in terms of the number of incorrect targets contacted per trial.

5.3 GENERAL PROCEDURE

Each subject received instructions from the experimenter and then performed an appropriate number of training trials. Following this, the experimental trials began with the subject commanding the end effector from an initial condition (IC) and contacting the center contact with the ESAM stylus. The signal denoting contact was sent to the digital event timer. After this initial contact, the experimenter verbally commanded the subject to move the effector to the designated target. The targets were coded 1, 2, 3 and 4 away from the center contact "0." That is, "left-3" meant moving away from 0 to the third target on the left. When the subject made contact with the commanded target, a signal terminated timekeeping on a digital clock in the experimenter's station. The digital clock was active from the time contact with the center contact was broken until contact was made with the designated target. After contact, the experimenter verbally commanded the subject to return the stylus to the IC position and proceed to the next trial.

Each subject completed 16 separate trials per task board orientation before proceeding to the next board orientation. The task board orientations are shown in Figure 5-2. Trial presentation was randomized over subjects, and the task board orientation presentation was randomized by subject.

5.4 TEST SUBJECTS

Five male subjects were used for this testing program. Each subject had extensive testing experience using this manipulator system (each had completed a minimum of 200 trials/manipulator). All subjects were right hand dominant, between 21-45 years of age, had 20/20 corrected vision, and had engineering backgrounds.

5.5 RESULTS

The raw data from this test series were subjected to a four way analysis of variance which assumed a treatment-by-subject experimental design with all factors fixed except subjects. The three dependent measures were individually subjected to an analysis of variance. The resulting source data are presented in Tables 5-1 through 5-3.

5.5.1 Response Time Analysis

Analysis of this dependent measure revealed three significant levels of interaction of elapsed time from center contact to designated target. Table 5-1 shows the main effects of quadrant (grouping of same size targets) and target location which revealed a signifigance level of P<.01. The joint interaction of board position by quadrant (target size) reached a P<.05 level of signifigance. The data are presented in Figures 5-3 through 5-5.

Figure 5-3 presents the main effect of quadrant (target size) which reveals a steady decrease in response time as a function of increasing contact area.

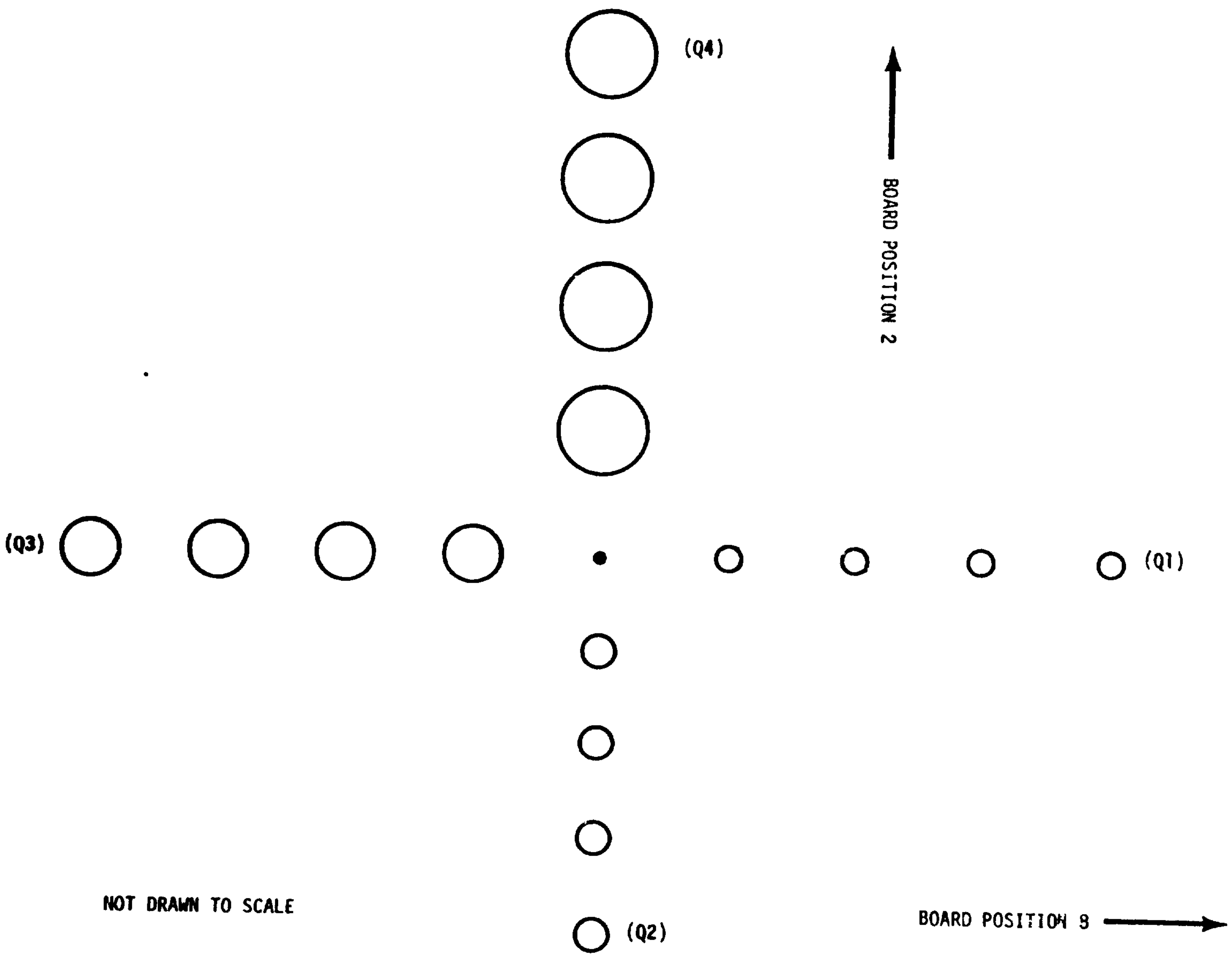


Figure 5-2: Minimum Position Board Orientation

Table 5-1: Analysis of Variance for Response Time

SOURCE	SUM OF SQUARES	dF	MEAN SQUARE	F
MEAN	13082.54	1	13082.54	68.67
CAMERA ANGLE (C)	20.55	1	20.55	.64
BOARD (B)	.03	1	.03	.01
QUADRANT (Q)	457.56	3	152.52	20.67**
TARGET (T)	1106.94	3	368.99	18.92**
SUBJECTS (S)	762.06	4	190.52	
CB	3.81	1	3.81	.84
CQ	2.52	3	.84	.14
BQ	75.97	3	25.32	4.02*
CT	19.05	3	6.35	.59
BT	17.99	3	6.00	.57
QT	117.42	9	13.05	1.20
CS	128.52	4	32.13	
BS	227.27	4	56.82	
QS	88.53	12	7.38	
TS	234.02	12	19.50	
CBQ	104.99	3	35.00	3.07
CBT	90.88	3	30.29	2.09
CQT	73.09	9	8.12	1.15
BQT	68.60	9	7.62	.92
CBS	18.16	14	4.54	
CQS	72.07	12	6.00	
BQS	75.53	12	6.29	
CTS	128.37	12	10.70	
BTS	125.94	12	10.49	
QTS	390.66	36	10.85	
CBQT	86.95	9	9.66	.75
CBQS	136.96	12	11.41	
CBTS	173.60	12	14.47	
CQTS	254.58	36	7.07	
BQTS	297.89	36	8.27	
CBQTS	461.05	36	12.81	

** $P<.01$
* $P<.05$

Table 5-2: Analysis of Variance for Errors

SOURCE	SUM OF SQUARES	dF	MEAN SQUARE	F
MEAN	16.65	1	16.65	32.01
CAMERA ANGLE (C)	.08	1	.08	.19
BOARD (B)	.38	1	.38	1.90
QUADRANT (Q)	.43	3	.14	.60
TARGET (T)	.18	3	.06	.36
SUBJECTS (S)	2.08	4	.52	
CB	.01	1	.01	.01
CQ	.56	3	.19	.74
BQ	1.31	3	.44	1.37
CT	.41	3	.14	.80
BT	.36	3	.12	.87
QT	2.78	9	.31	.76
CS	1.66	4	.41	
BS	.79	4	.20	
QS	2.89	12	.24	
TS	2.02	12	.17	
CBQ	.43	3	.14	.71
CBT	.18	3	.06	.35
CQT	2.60	9	.29	1.63
BQT	3.20	9	.36	1.77
CBS	1.17	4	.29	
CQS	3.02	12	.25	
BQS	3.83	12	.32	
CTS	2.04	12	.17	
BTS	1.66	12	.14	
QTS	14.71	36	.41	
CBQT	2.23	9	.25	1.24
CBQS	2.46	12	.20	
CBTS	2.08	12	.17	
CQTS	6.38	36	.18	
BQTS	7.22	36	.20	
CBQTS	7.19	36	.20	

** $P<.01$
* $P<.05$

Table 5-3: Analysis of Variance for IC to Center Contact

SOURCE	SUM OF SQUARES	dF	MEAN SQUARE	F
MEAN	9.901	1	9.901	61.75
CAMERA ANGLE (C)	.096	1	.096	2.41
BOARD (B)	.014	1	.014	.51
QUADRANT (Q)	.008	3	.003	.73
TARGET (T)	.028	3	.010	3.20
SUBJECTS (S)	.640	4	.160	
CB	.005	1	.005	.75
CQ	.012	3	.004	1.54
BQ	.016	3	.005	2.55
CT	.019	3	.006	1.02
BT	.056	3	.018	2.43
QT	.075	9	.008	2.25*
CS	.159	4	.040	
BS	.107	4	.027	
QS	.043	12	.004	
TS	.036	12	.003	
CBQ	.006	3	.002	.44
CBT	.031	3	.010	2.31
CQT	.085	9	.009	1.31
BQT	.084	9	.009	1.15
CBS	.029	4	.007	
CQS	.032	12	.003	
BQS	.025	12	.002	
CTS	.075	12	.006	
BTS	.092	12	.008	
QTS	.134	36	.004	
CBQT	.060	9	.007	.81
CBQS	.058	12	.005	
CBTS	.053	12	.004	
CQTS	.260	36	.007	
BQTS	.292	36	.008	
CBQTS	.299	36	.008	

** P<.01
 * P<.05

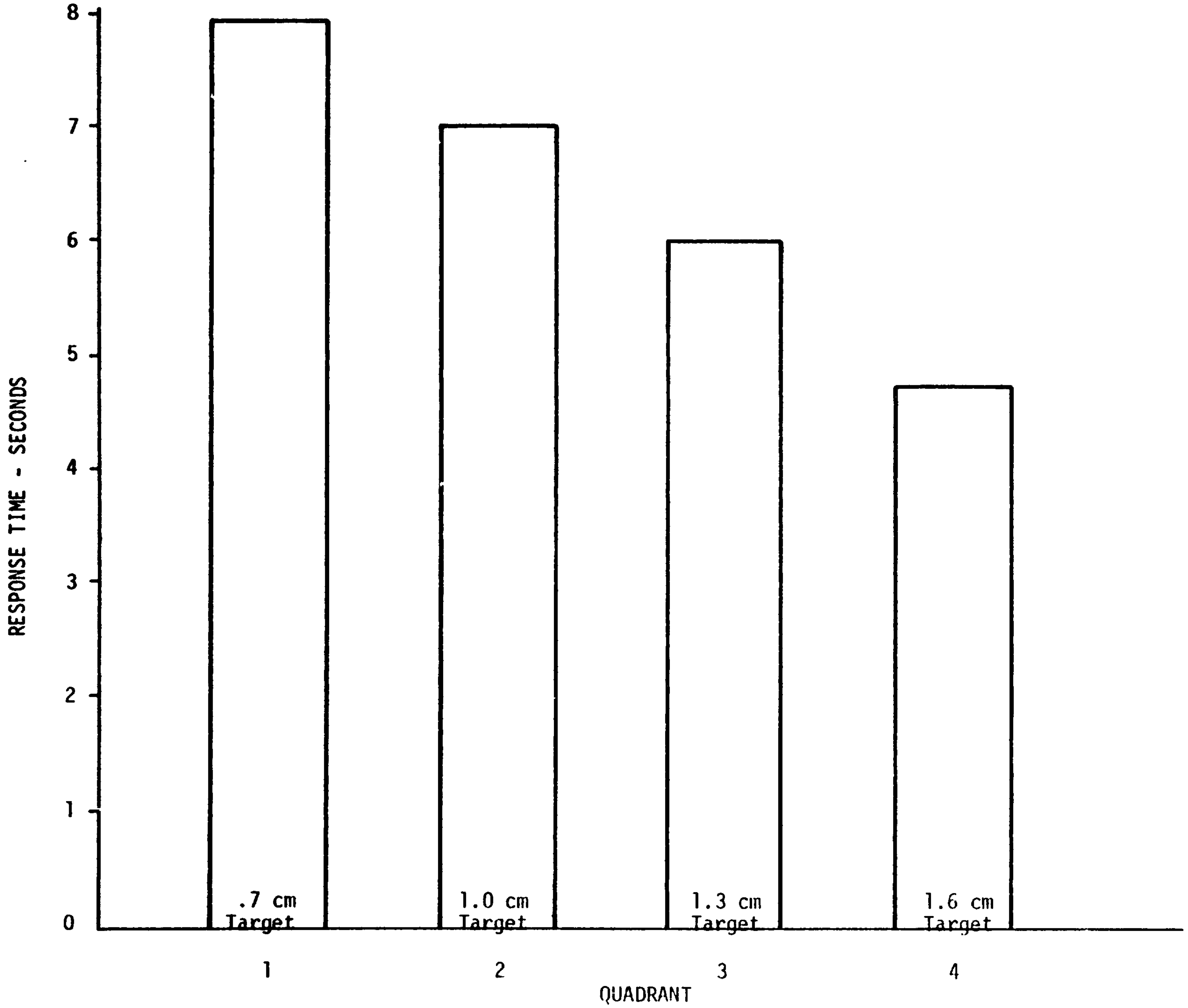


Figure 5-3: Main Effect of Quadrant (Target Size) on Response Time

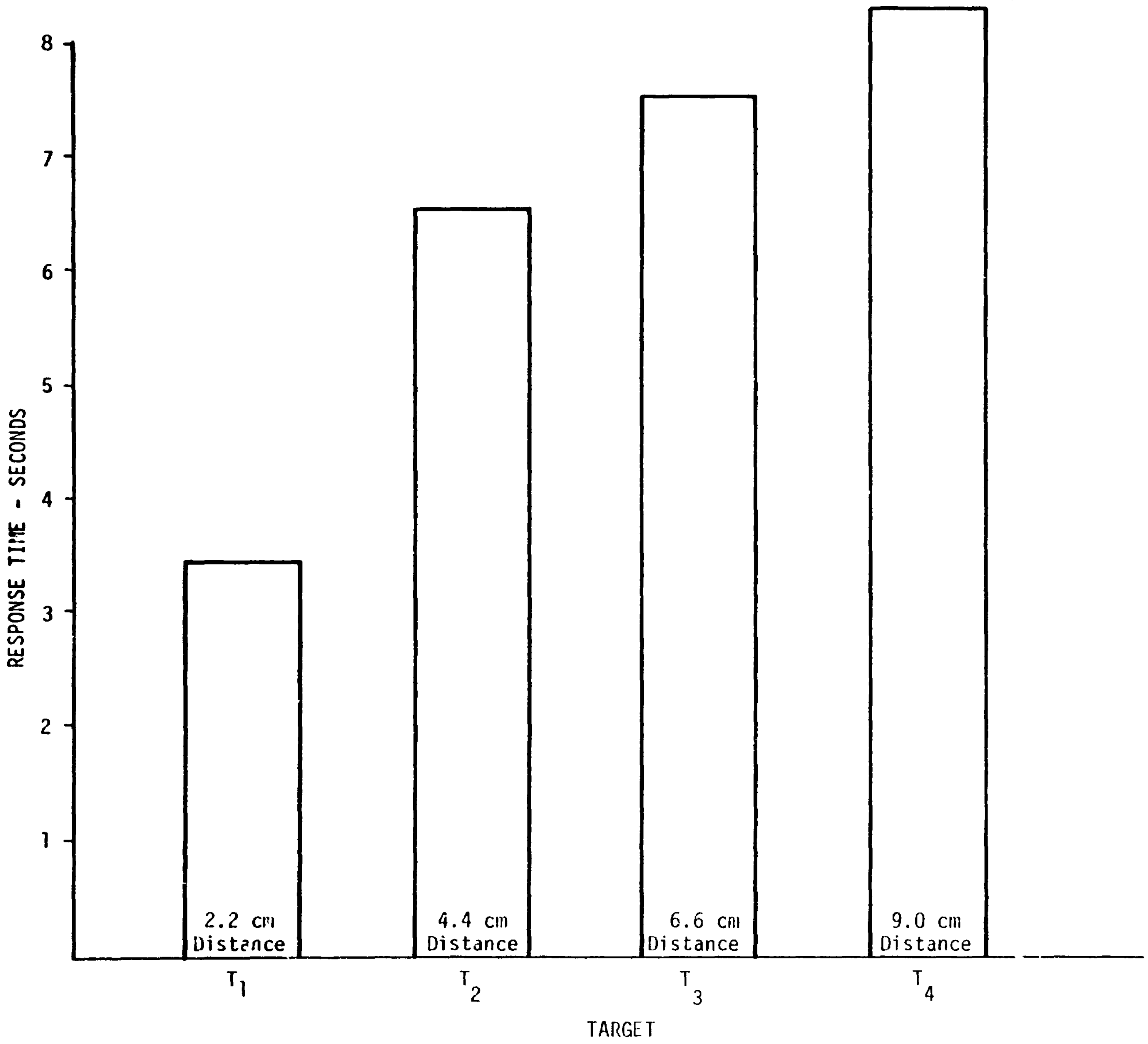
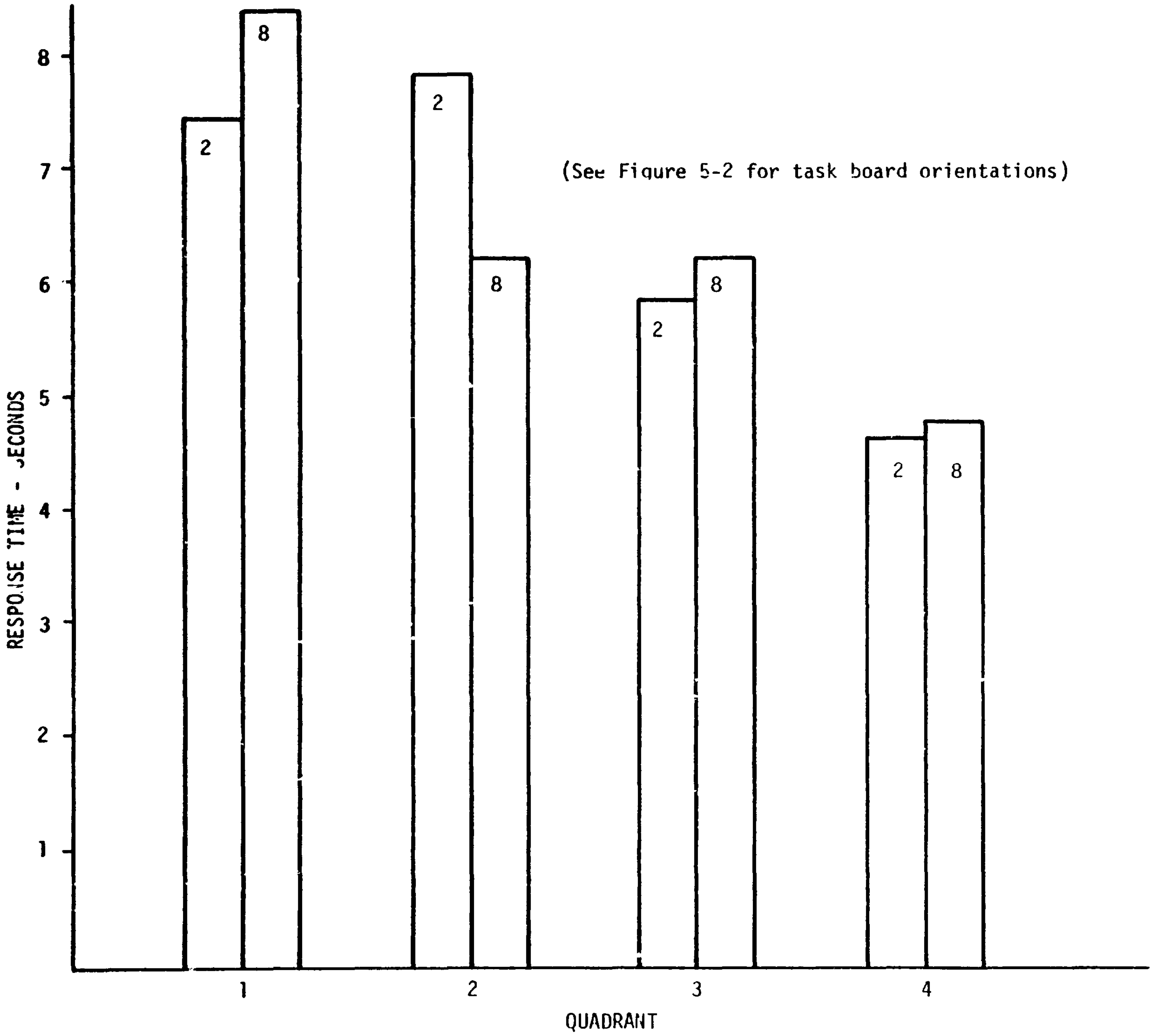


Figure 5-4: Main Effect of Target Location on Response Time



(See Figure 5-2 for task board orientations)

Figure 5-5: Interaction of Quadrant by Board Position on Response Time

Figure 5-4 illustrates that distance from the center contact affects the travel time. Therefore, response time increases as a function of distance traveled. However, another explanation could be that with shorter travel, fewer shoulder and arm muscles were involved by the operator therefore allowing finer control by the hand and wrist muscles. In addition, as the operator increased the travel distance, he had to move more mass of the controller which, although the controller was spring-assisted, required overcoming slight inertia in both starting and stopping the controller.

Figure 5-5 shows the joint interaction of board position by quadrant (target size) which depicts that in general, response time decreases as a function of increasing target size. The data also show that lateral movements were always less than vertical movements.

5.5.2 Error Analysis

The number of errors per trial made by the subject while moving the stylus from IC to designated target was submitted to an analysis of variance. These data are presented in Table 5-2. No significant levels of difference were found. Therefore, the data are only presented for information purposes.

5.5.3 IC to Center Contact Analysis

This is a measure of the time required by the subject to move the ESAM stylus from the IC position to the center contact. Ideally, this measure should exhibit an extremely small variance since the distance traveled and the center contact locations were identical in all trials.

Table 5-3 presents the analysis which shows that the interaction of quadrant, or target size, by target location reached a significant level of $P < .05$. These data are presented graphically in Figure 5-6. Theoretically, these execution times should be identical for all cases. However, it is evident

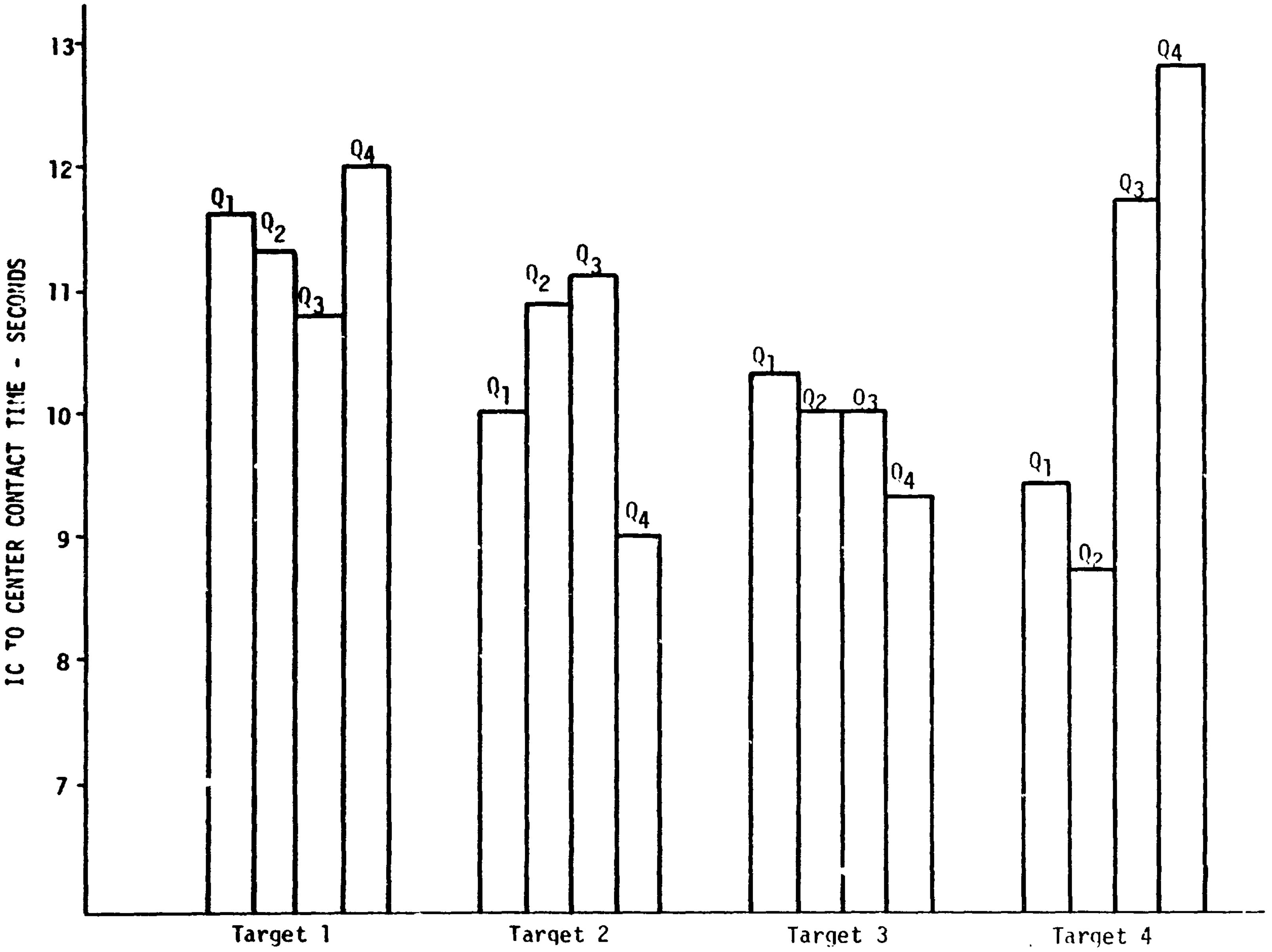


Figure 5-6: IC to Center Contact Response Time for Target Location by Quadrant

that the subject's response times were influenced by the location and size of the designated targets as evidenced by the tight variance in time of targets 1 and 3 across all quadrants (1.2 and 1.0 seconds respectively). Conversely, the time required to contact targets 2 and 4 each exhibited a greater range of 2.1 and 4.1 seconds respectively. When the data are examined by quadrants, then 2 and 4 again show the greatest variance (2.6 and 3.8 seconds respectively) with quadrant 3 showing a 1.7 second range.

In examining the data, it appears that the location of the outermost targets (number 4) exhibited the greatest variation in time (4.1 seconds). This was perhaps due to the subject's knowledge he would travel a greater distance; therefore, he altered his closure rate and angle of travel to provide him with a better approach to the designated target.

The differences in performance measures due to the variation in camera position were not found to be statistically significant. This result was anticipated since the availability of depth cues should reduce the strong dependence of performance on camera position which occurs for some manipulator and visual estimation tasks.

6.0 DEXTERITY TEST

6.1 TEST OBJECTIVE

The objective of this experiment was to determine a human operator's capability to grasp, control and fine position various size objects using a six degree-of-freedom ESAM with the analog joystick controller and a stere-optic television system.

6.2 APPARATUS

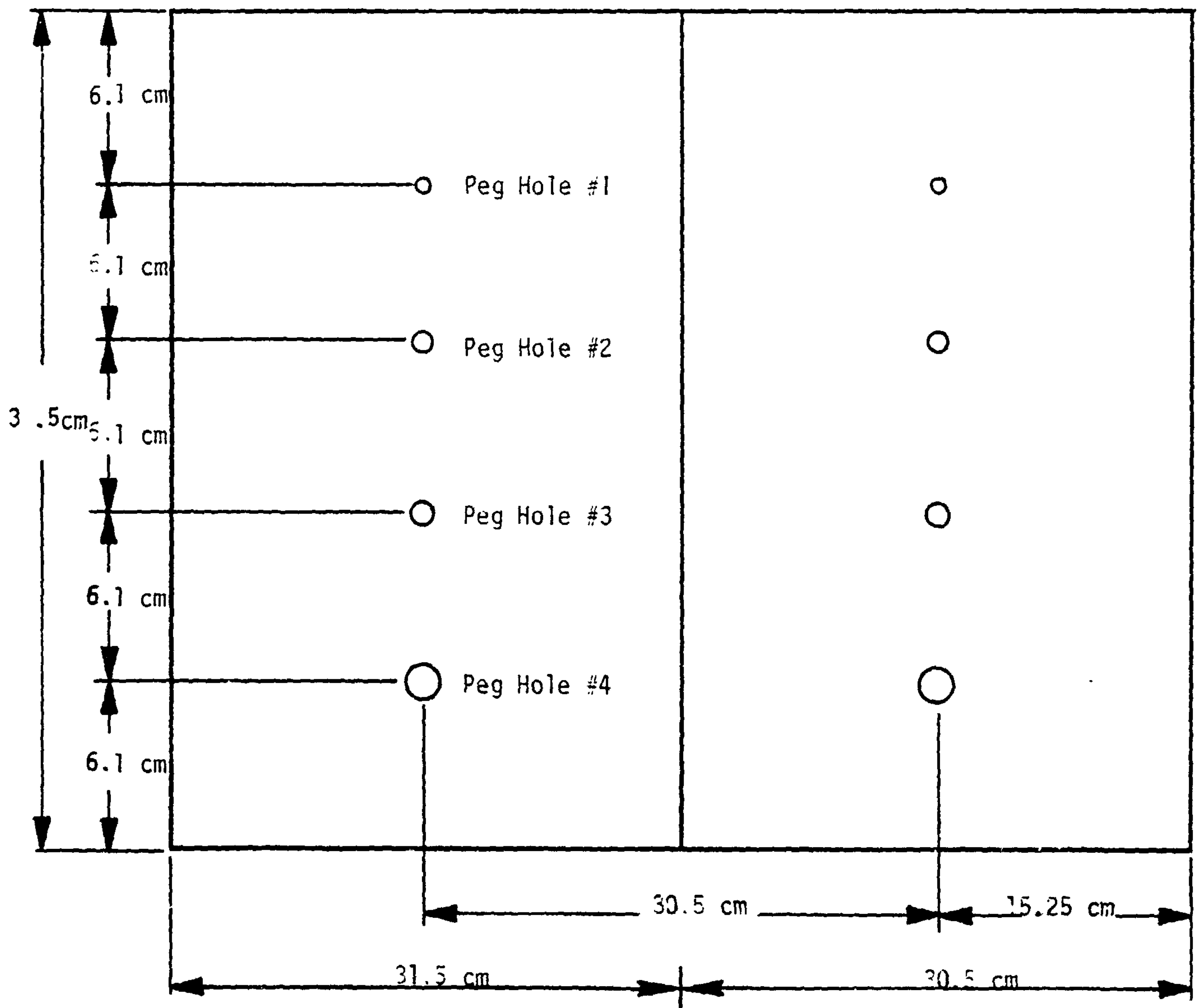
The task boards were two 30.5 cm square (one foot square) spring-mounted, mechanically-joined task boards each containing a single vertical row of four holes (see Figure 6-1). The four holes were of different diameters with the smallest hole designated number 1, at the top and increasing in diameter to the largest, designated number 4, at the bottom. Each hole had a corresponding size peg (see Figure 6-2 for peg dimensions) which, when removed from one board, started a timer and when replaced in the other, stopped the timer to record elapsed time. Each hole was surrounded by a 0.31 cm (.12 in.) white ring to facilitate television viewing. Figure 6-3 shows the dexterity test setup.

The boards could be reversed electrically so either left-to-right or right-to-left removal and replacement transfer times could be measured.

6.3 EXPERIMENTAL DESIGN

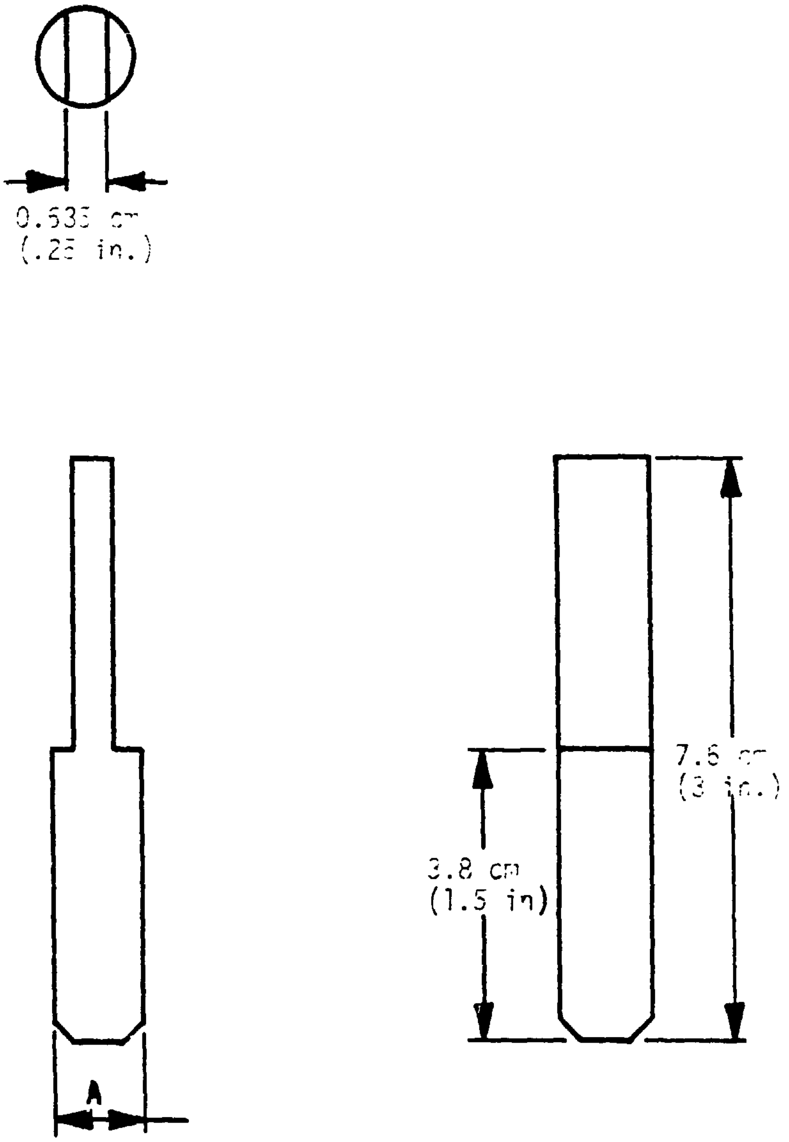
During the test, several variables were used to determine the effect on task time. The independent variables were:

- Peg hole diameters
  1) 9.53 mm
  2) 12.70 mm
  3) 15.88 mm
  4) 19.05 mm



PEG HOLE	CORRESPONDING PEG
1 = ○ 9.5 mm	7.9 mm
2 = ○12.9 mm	11.1 mm
3 = ○15.9 mm	14.3 mm
4 = ○19.1 mm	17.5 mm

Figure 6-1 Dexterity Test Task Module



Dim A: Peg 1 = 7.94 mm (0.312 inch)
Peg 2 = 11.11 mm (0.437 inch)
Peg 3 = 14.29 mm (0.563 inch)
Peg 4 = 17.46 mm (0.688 inch)

Figure 6-2: Dexterity Test Target Pegs

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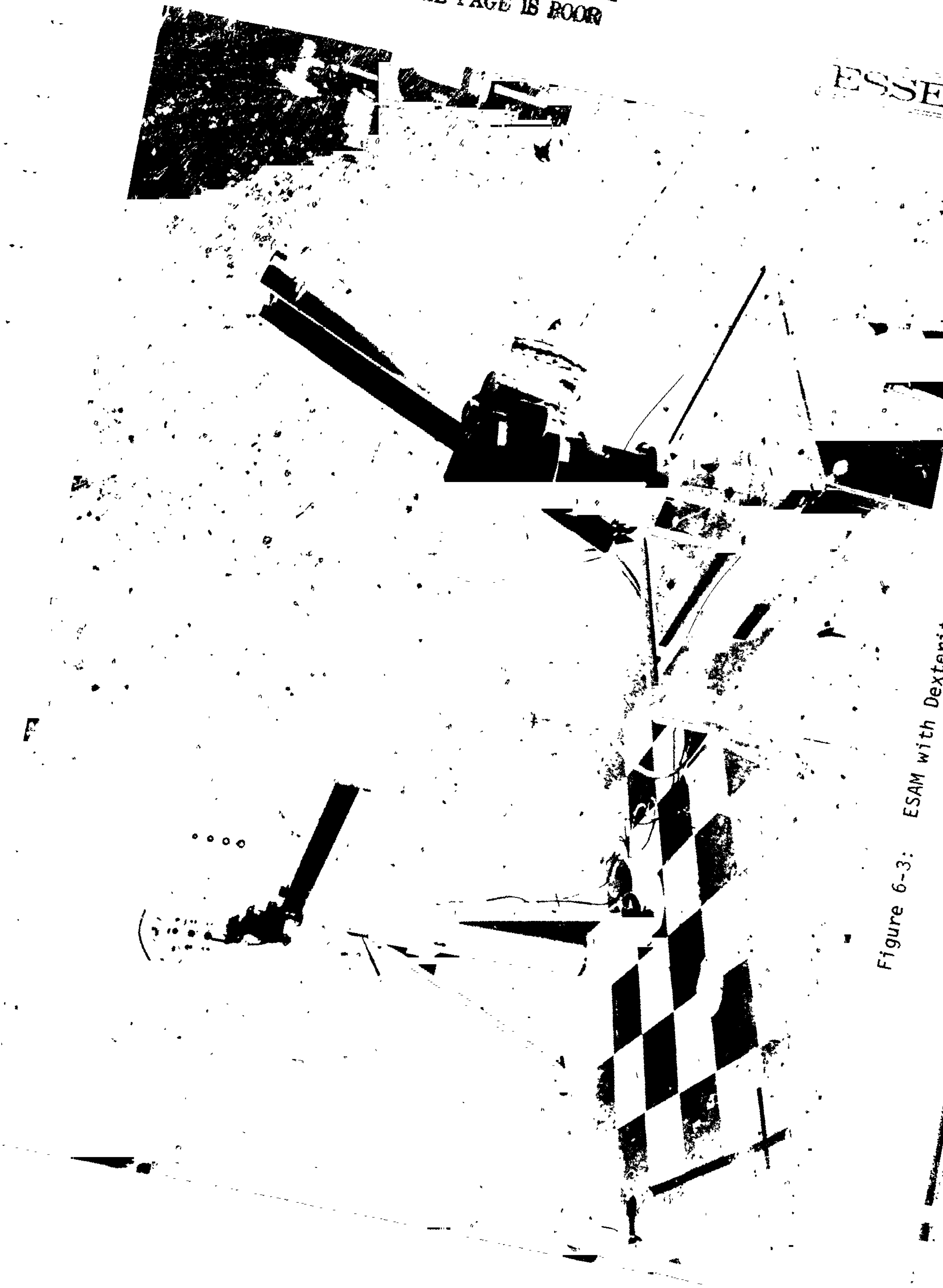

Figure 6-3: ESAM with Dexterity Test Board

- Peg diameters

    1) 7.94 mm
    2) 11.11 mm
    3) 14.29 mm
    4) 17.46 mm

- Directions of peg transfer movement

    Right remove - left replace
    Left remove - right replace

- TV camera location

    1) Camera 1 - 0° offset with respect to ESAM longitudinal axis and mounted on a floor mounted pedestal behind the arm. The camera base plate incorporated an 8° pitch down angle.

    2) Camera 2 - 0° offset with respect to ESAM longitudinal axis and mounted to the ESAM at the center line of the shoulder azimuth and elevation joint. The camera base plate incorporated a 5° pitch down angle.

- TV geometry (see Figure 6-4 for stereo camera geometry)

    1) Camera 1 - Floor mounted camera system
    Range = 241.3 cm (95 in.)
    Convergence = 147.3 cm (58 in.)
    Baseline = 12.06 cm (4.75 in.)
    Target = 7.6 cm (3.0 in.)
    Image = 2.5 (1.0 in.)
    K (Field of View) = IR/T = 80.44 cm (24.67 in.)
    D (Disparity) = BK/C - BK/R = 1.01

    2) Camera 2 - ESAM mounted camera system
    Range = 187.96 cm (74 in.)
    Convergence = 121.9 cm (48 in.)
    Baseline = 12.06 cm (4.75 in.)
    Target = 7.6 cm (3.0 in.)
    Image = 2.5 cm (1.0 in.)
    K (Field of View) = IR/T = 62.65 cm (24.76 in.)
    D (Disparity) = BK/C - BK/R = 0.86.

The control variables were:

- TV parameters

    1) Analog signal format - 4.5 MH.
    2) 32 db S/N ratio

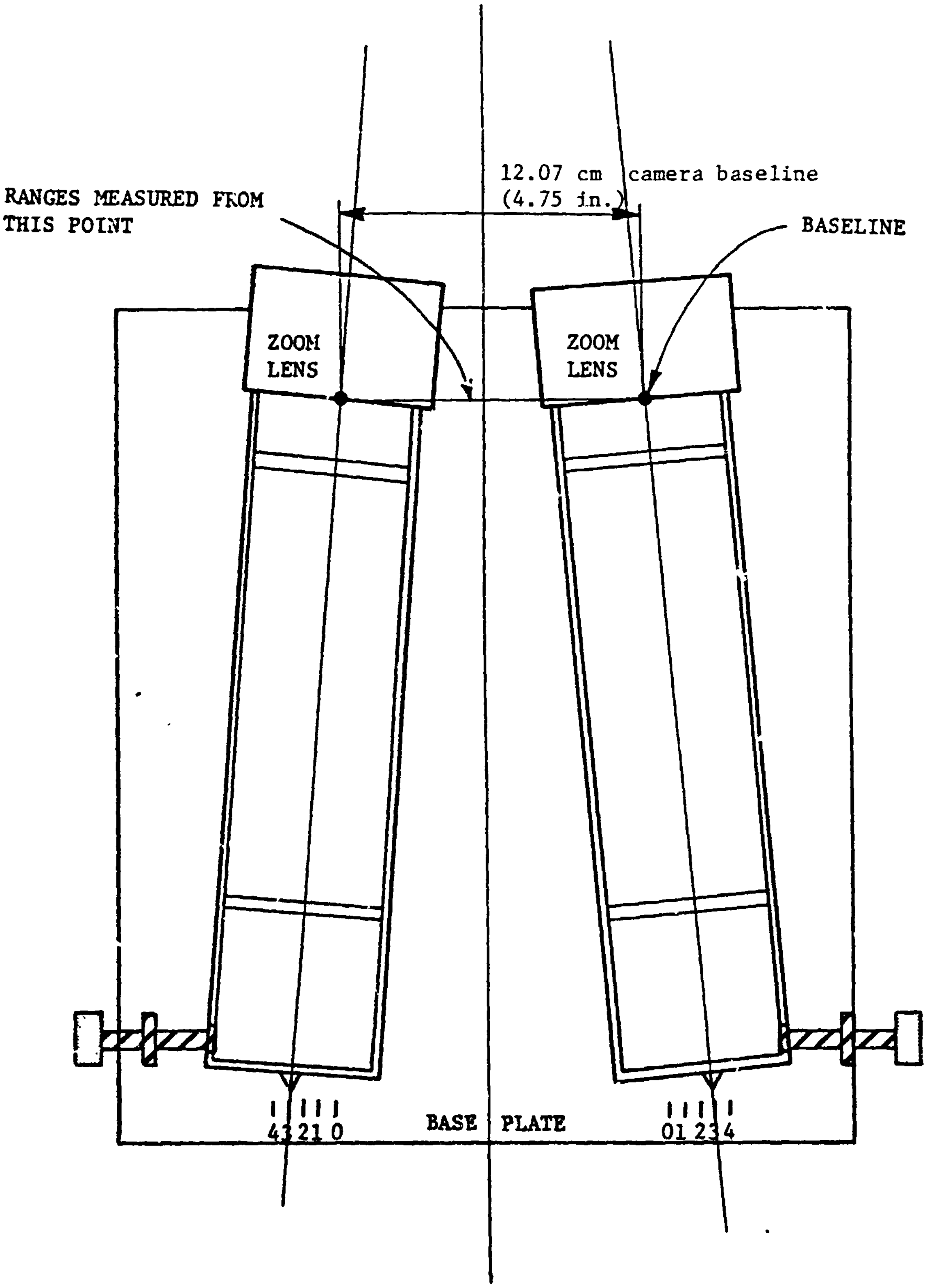

Figure 6-4: Overhead View of Stereo Camera Pair and Base Plate

- Video signal parameters using Tektronix RM 529 Waveform monitor with a standard (composite NTSC) 140 units - 1 volt video scale:

  1) Background less than or equal to 10 units
  2) 40 units $\leq$ maximum white level $\leq$ 60 units

- Subject monitor

  1) Brightness control set such that background level is below CRT cutoff
  2) Contract set to achieve satisfactory viewing level. This level to be set initially, measured with Tektronix J16 Digital Photometer, and maintained throughout all testing.

- Travel distance: From end effector jaws to center of task board was a mean of 50.8 cm (20.0 in.)

- Peg hole clearance: 1.59 mm for each peg (0.63 in.)

- Ambient lighting at task board: Minimum of 100 foot candles.

The dependent variables measured during each test run were:

- Elapsed time from arm IC to peg removal signal

- Elapsed time (transfer time) from peg removal signal to peg replacement signal.

6.4 TEST PROCEDURE

Each subject was read the task instructions by the experimenter and then performed an appropriate number of training trials using the stereoptic television system before actual data collection took place. During testing, each trial began with the experimenter directing the subject to remove and replace a designated peg (i.e., "Remove and replace Peg 3"). The subject then commanded the manipulator end effector from a preset initial condition (IC) to the designated peg area, grasped and removed the peg. The time for his IC to peg removal was recorded and the peg removal itself generated an electrical signal which started the remote digital timer. The subject then transferred the peg to the corresponding hole in the replace module and inserted it in the hole. When the peg had been inserted 1.25 cm (0.5 in.) into the hole, it closed an electrical circuit and stopped the timer which the experimenter recorded as the transfer time. After peg replacement, the experimenter instructed the subject to return to the initial condition.

The subjects participating in this experiment also participated in the previous dexterity test (Ref. 4); therefore, they were familiar with the test procedures. Each subject completed 16 individual trials at each of the two camera locations which included two blocks of eight transfers each using two directions of transfer.

6.5 RESULTS AND CONCLUSIONS

The raw data from the two dependent measures were subjected to a four-way analysis of variance with all factors fixed except subjects. This type of analysis assumed a treatments-by-subjects design. The resulting source tables are presented in Tables 6-1 and 6-2.

The IC to peg removal analysis indicated the main effect of peg size reached a significant level of P<.01. These data are graphically presented in Figure 6-5. By inspection, this figure reveals the smallest peg (number 1) required the greatest mean travel time which decreased as a function of increasing peg size. This appears to be explained partly by the size of the object grasped and partly because the extension of the ESAM was slightly greater for the smaller pegs (1 and 2) than the larger pegs (3 and 4) which are rather tightly grouped (<1.0 second difference) when compared with pegs 1 and 2. When these data are compared with that from the previous dexterity tests (using two orthogonal monoptic cameras), the smallest peg again consumed the greatest travel time and the largest peg consumed the least time.

Table 6-1: IC to Peg Removal Analysis of Variance

SOURCE	SUM OF SQUARES	MEAN SQUARE	dF	F
MEAN	39270.16	39270.16	1	215.54
CAMERA LOCATION (C)	8.78	8.78	1	.07
TRANSFER DIR (D)	4.75	4.75	1	.33
PEG (P)	409.78	136.59	3	11.49**
SUBJECTS (S)	728.78	182.19	4	
CD	.03	.03	1	.01
CP	53.31	17.17	3	.86
DP	3.03	1.01	3	.10
CS	529.28	132.32	4	
DS	58.14	14.53	4	
PS	142.63	11.89	12	
CDP	40.81	13.60	3	2.20
CDS	48.80	12.20	4	
CPS	249.30	20.77	12	
DPS	123.26	10.27	12	
CDPS	74.05	6.17	12	

Table 6-2: Transfer Time Analysis of Variance

SOURCE	SUM OF SQUARES	MEAN SQUARE	dF	F
MEAN	42116.16	42116.16	1	100.67
CAMERA LOCATION (C)	21.42	21.42	1	.22
TRANSFER DIR (D)	268.64	268.64	1	11.35*
PEG (P)	2732.14	910.72	3	33.22**
SUBJECTS (S)	1673.44	418.36	4	
CD	120.54	120.54	1	1.31
CP	152.00	50.67	3	2.62
DP	87.10	29.03	3	.96
CS	391.38	97.84	4	
DS	94.66	23.67	4	
PS	328.92	27.41	12	
CDP	71.67	23.89	3	
CDS	367.06	91.77	4	
CPS	231.87	19.32	12	
DPS	361.77	30.15	12	
CDPS	334.34	27.86	12	

* $P<.05$

** $P<.01$

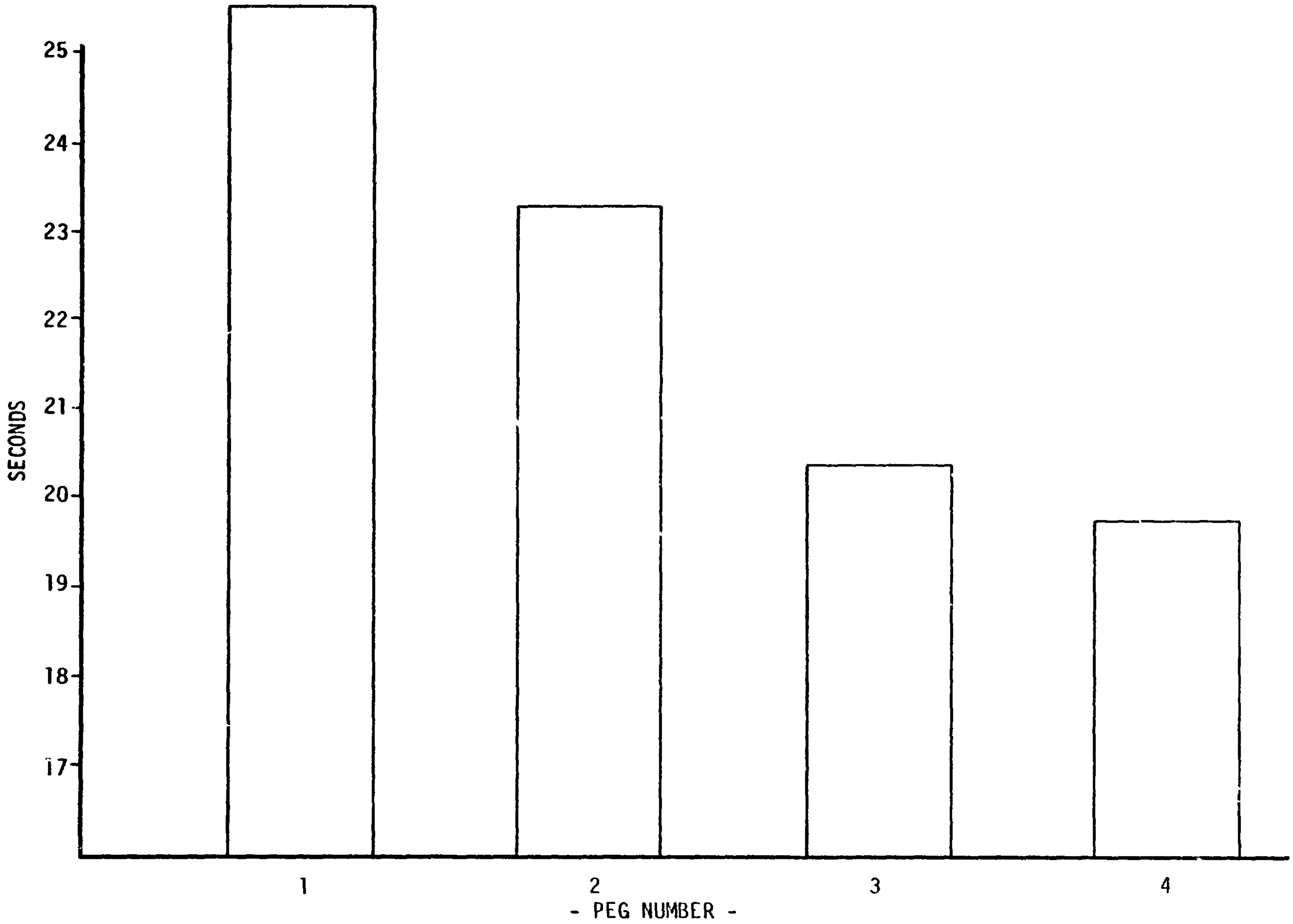

Figure 6-5: IC to Peg Remove Elapsed Time as unction of Peg Size

However, the two interior pegs (2 and 3) changed ranking in that peg 3 required nearly three seconds longer than peg 2, and this peg nearly equalled the time of peg 4. Overall, the mean travel time using the monoptic camera system was less than the stereoptic camera system which may have implication for further study. However, the frequency of errors in both tests was very low.

The transfer time analysis of variance revealed that both transfer direction and peg size reached significant levels of difference. Response time as a function of transfer direction is illustrated in Figure 6-6. This figure shows that going from left to right consumed less time (a difference of nearly four seconds) than right to left. This appears to be the effect of the stereo camera system coupled with right-handed subjects. The previous dexterity test data for the same conditions also revealed longer response times and the opposite effect (transfer left time was shorter). The response time was also much shorter for the stereo camera system overall (28 seconds vs. 41 seconds) when compared with the orthogonal monoptic system. The greatest change is in the transfer right direction which showed nearly a 53 per cent reduction whereas the transfer left reduction was nearly 35 per cent. The mean reduction in time, overall, was nearly 32 per cent which has tremendous implications for timelining of payload operations and key events.

Response transfer time as a function of peg size reached a level of significance at the $P<.001$ level. These data are presented in Figure 6-7. The smallest peg (number 1) showed the greatest transfer time and the largest peg (number 4) showed the shortest transfer time. The difference between these two pegs reached nearly 50 per cent reduction. This decrease in

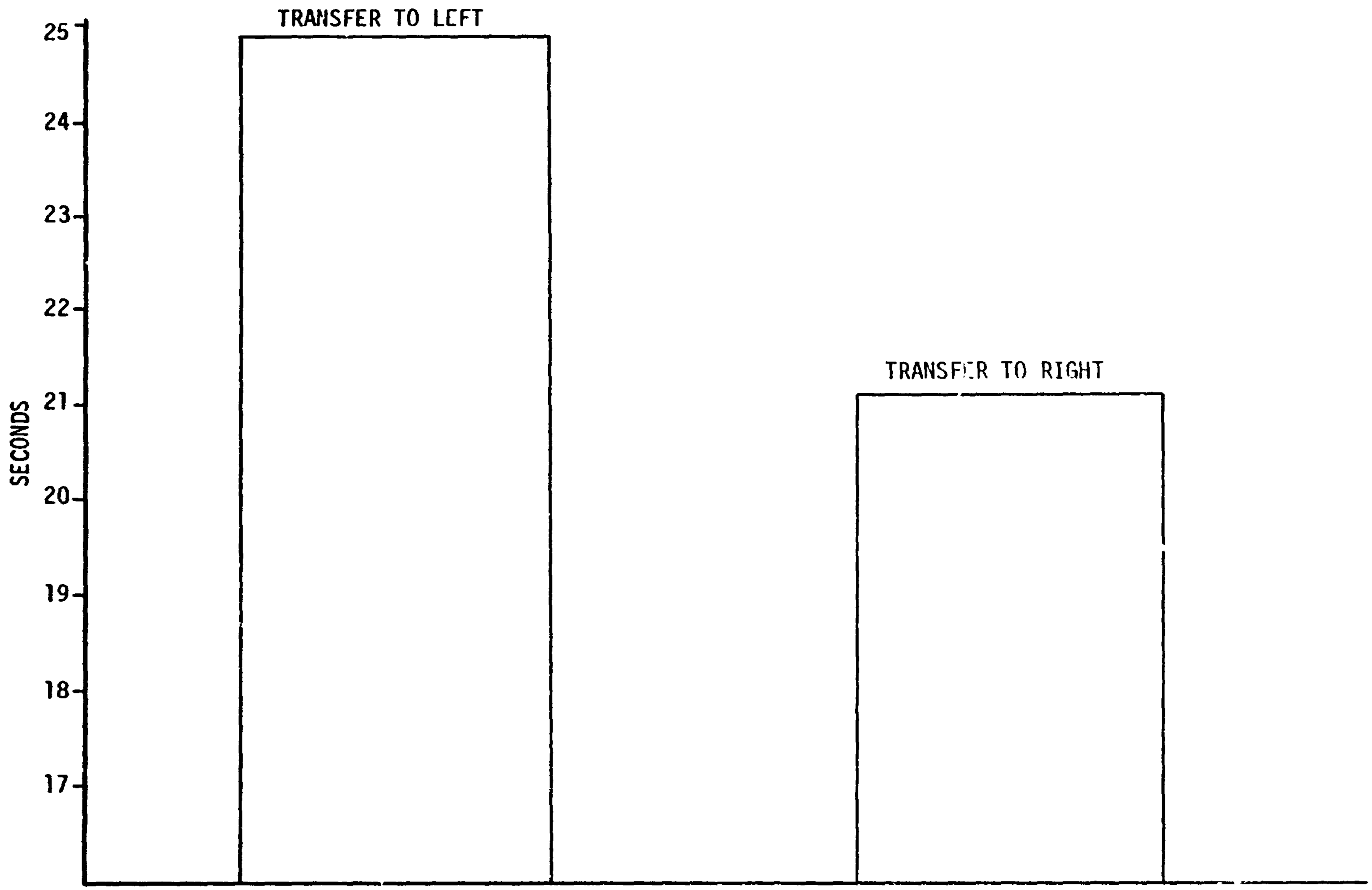

Figure 6-6: Response Time as a Function of Direction of Transfer

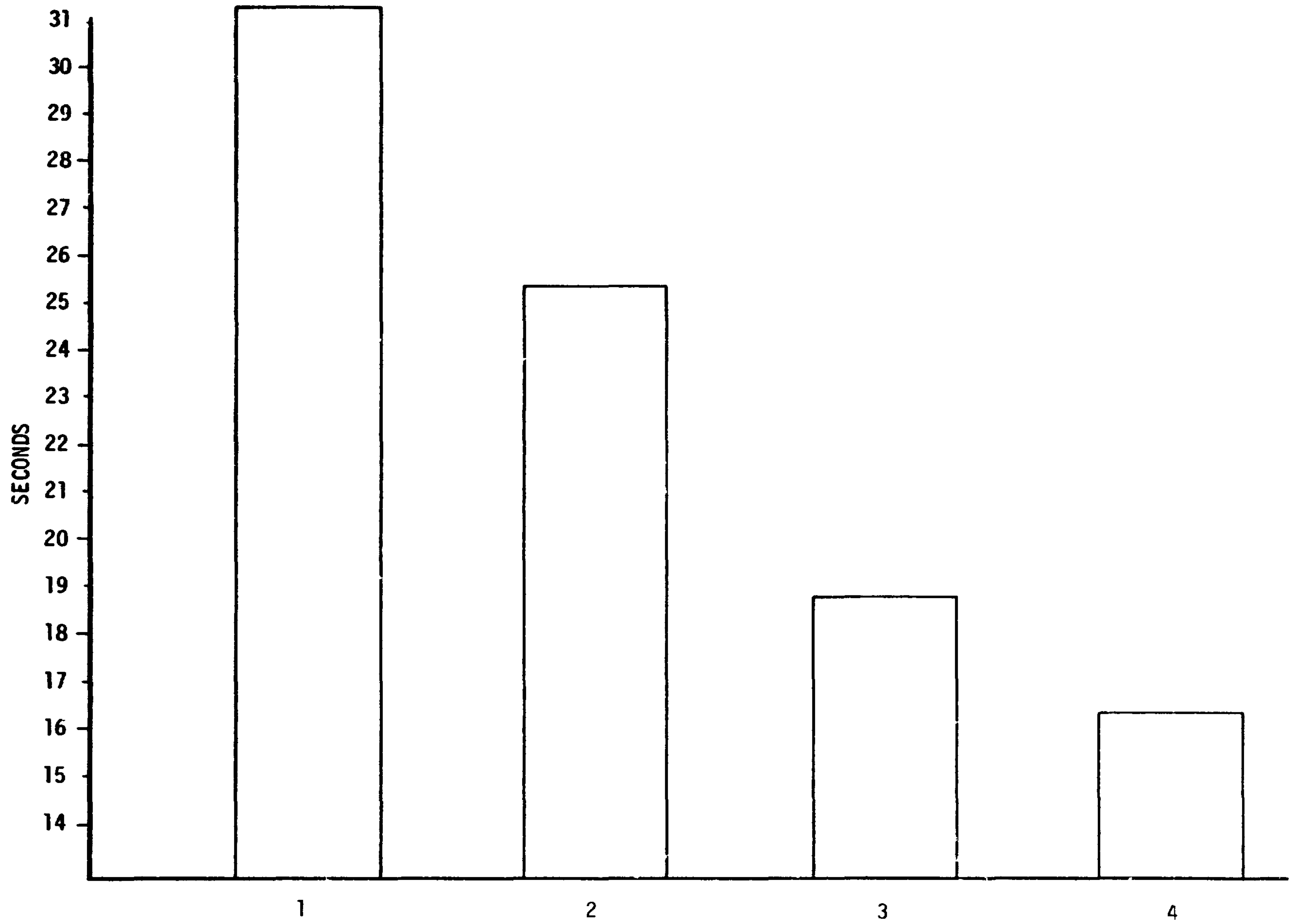

Figure 6-7: Response Time as a Function of Peg Size

response time as a function of increasing peg size could be due to the position of the pegs relative to the manipulator. This is supported by the fact that extension/retraction was less for pegs near the bottom of the board when compared to the pegs nearer the top of the board. However, when these data are compared with that from the previous dexterity test, the smaller pegs (1 and 2) showed a reduction in transfer times of 26 per cent and 27 per cent respectively, and the larger pegs (3 and 4) showed a 42 per cent and 53 per cent decline respectively. The only difference between these two tests was the stereoptic camera system versus a two-monoptic, orthogonally-mounted camera system.

In general, it appears the addition of a stereo camera system to the ESAM/analog controller combination aids in defining more precisely the operating characteristics relative to the size of the object being handled.

7.0 GENERAL DISCUSSION AND CONCLUSION

The primary objective of the testing program described in this report was to determine if a stereoptic system would enable the operator to perform fine positioning and controlling tasks with a reduced operating time and with an equal or fewer number of errors than when using the two monoptic cameras. Any reduction in operating time with no increase in error rate should enhance the teleoperator operating characteristics by reducing the time required for teleoperator servicing tasks. This would simplify the teleoperator operator's job and increase the probability of mission success.

7.1 ERROR RESPONSE

The minimum position change total errors and error rates were examined first, since accuracy of movement for the total system is the single most important criterion for the total system and serves as a useful figure-of-merit. The total error count from the previous study (Ref. 4), using two orthogonally-mounted monoptic cameras, was 39 errors distributed over 160 trials for an error rate of 24 per cent. When these data are compared with the present data distributed over 320 trials (two camera locations were used), the total error count was 34 for camera location 1 and 39 for camera location 2 with a mean value of 36 errors. The error rate by camera location was 21 per cent and 29 per cent for camera location 2, yielding a mean error rate of 23 per cent, which satisfies the criterion of accuracy by maintaining a low error count.

The total error count and the error rate for the dexterity test using both video systems were not subjected to an analysis since the frequency of errors (defined by a peg being dropped) rarely occurred after the addition of the wrist yaw to the ESAM (Ref. 4, Section 6.0).

7.2 RESPONSE TIME

A summary of the primary features of ten manipulator system tests conducted to date is given in Table 7-1. The data shown are mean response times for fine manipulator positioning movements. For the minimum position change test, this is defined as the time for moving from the center contact to the designated target, and for the dexterity test as peg removal to peg replacement time.

The overall mean response time for the previous minimum position change test (Ref. 4, Section 7.0) was 10.83 seconds, whereas the current data (averaged over two camera locations; see Section 5.3 of this report) was 6.39 seconds which reveals a 41 per cent decrease in response time by using a stereoptic viewing system.

The overall mean transfer time for the previous dexterity test (Ref. 4, Section 6.0) was 40.35 seconds which included both directions of transfer whereas the current data (averaged over two camera locations; see Section 6.3 of this report for locations) was 22.95 seconds. This reveals a 43 per cent reduction in response time by using a stereoptic viewing system.

Based upon these data, it appears that the stereoptic viewing system seems to enhance the effect of the dedicated controller on the ESAM to produce a marked reduction in response time with no tradeoffs in overall system accuracy. The question to be resolved is whether an isotonic or isometric controller, packaged to satisfy the Shuttle volume constraints, in conjunction with the ESAM will also achieve comparable reduction in operating time while yielding no increase in errors. This problem is being defined and work has already begun to interface the ESAM with smaller controllers.

Table 7-1: SUMMARY OF MANIPULATOR TESTS

TEST SERIES	MANIPULATOR SYSTEM	CONTROLLER	VISUAL SYSTEM	TEST	MEAN TASK TIME
1	5 DOF, ESAM	ANALOG JOYSTICK CONTROLLER	2 ORTHOGONAL MONOPTIC CAMERAS	MINIMUM POSITION CHANGE	11.39 SEC.
2	RAM	TERMINAL POINTER CONTROLLER	2 ORTHOGONAL MONOPTIC CAMERAS	MINIMUM POSITION CHANGE	37.25 SEC.
3	5 DOF, ESAM	REPLICA JOYSTICK CONTROLLER	2 ORTHOGONAL MONOPTIC CAMERAS	MINIMUM POSITION CHANGE	10.83 SEC.
4	5 DOF, ESAM	TERMINAL POINTER CONTROLLER	2 ORTHOGONAL MONOPTIC CAMERAS	MINIMUM POSITION CHANGE	16.05 SEC.
5	RAM	MODIFIED TERMINAL POINTER CONTROLLER	2 ORTHOGONAL MONOPTIC CAMERAS	MINIMUM POSITION CHANGE	20.40 SEC.
6	RAM	ISOMETRIC CONTROLLER	2 ORTHOGONAL MONOPTIC CAMERAS	MINIMUM POSITION CHANGE	25.00 SEC.
7	RAM	MODIFIED ISOMETRIC CONTROLLER	2 ORTHOGONAL MONOPTIC CAMERAS	MINIMUM POSITION CHANGE	18.7 SEC.
8	6 DOF, ESAM	ANALOG JOYSTICK CONTROLLER	2 ORTHOGONAL MONOPTIC CAMERAS	DEXTERITY	40.35 SEC.
9	6 DOF, ESAM	ANALOG JOYSTICK CONTROLLER	STEREO SYSTEM	MINIMUM POSITION CHANGE	6.39 SEC.
10	6 DOF, ESAM	ANALOG JOYSTICK CONTROLLER	STEREO SYSTEM	DEXTERITY	22.95 SEC.

It appears reasonable, based on current data, that any remote manipulator controller concept will require: (1) separation of controller functions for fine control, and (2) an operator controlled stereo camera geometry configuration.

8.0 REFERENCES

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