EARTH ORBITAL TELEOPERATOR MANIPULATOR
SYSTEM EVALUATION PROGRAM

Test Report Number 2

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SUBJECT: 1974 Year End Reports, Earth Orbital Teleoperator Manipulator System Evaluation Program, Test Report Number 2 and Earth Orbital Teleoperator Visual System Evaluation Program, Test Report Number 3

Attached for your information is a copy of the Essex Corporation year end reports of the activities conducted in the MSFC Manipulator and Visual Systems facilities. These reports contain a synopsis of past activities and future plans in the manipulator and visual system areas.

Any questions, comments or request for additional copies of these reports, contact the undersigned at MSFC (205) 453-4271. Guerin

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1.0 INTRODUCTION

Teleoperator technology is presently being studied within NASA for on-orbit applications, including assembling of large structures, servicing and retrieval of satellites. The orbital teleoperator program is being conducted by MSFC and is designed to produce a suitable system for a series of Earth Orbital Teleoperator.

The orbital teleoperator system will include small dextrous servicing manipulators to be used in satellite servicing. The manipulator will perform tasks such as the removal and replacement of modules. Manipulator control and visual feedback will be carried out by remote data link with an operator located in the orbiter aft cabin or on the ground. The elements of a manipulator system therefore include the:

- manipulator arm and end effector
- control system
- visual system
- operator
- signal transmission

A portion of the MSFC effort is devoted to testing and development of technology in these areas. The intent is to determine optimal manipulator design in terms of configuration, number of joints, and operating characteristics. Coordinated with this effort is the study of control systems, visual systems, and man/system integration requirements.

The man/system integration effort is viewed as a primary factor in the teleoperator technology development area since the purpose of the teleoperator system is to extend man's capabilities into remote and hostile environments. To ensure that the man/machine interface aspects of the teleoperator program are adequately represented in the system design process, a joint NASA/ESSEX program of system/operator performance testing has been implemented. The general approach employed is to perform man-in-the-loop performance tests using existing manipulators and end effectors. Testing is planned so as to permit comparison of manipulator systems in terms of performance of standard tasks derived from servicing mission requirements. The tasks are performed with a trained operator in the loop providing control outputs and receiving feedback via a closed circuit television system. Tests are also designed to study performance effects resulting from changes in controller and/or control system parameters for a particular class of manipulator arms.

The derivation of the tasks to be used in testing, the general test plans, and the criteria to be utilized in manipulator system evaluation have been presented by Malone et al. (1973). The test program and the order of tests performed has been structured to provide system/operator performance data as a function of manipulator system parameters. These data will eventually be used to support design decisions in the development process leading to the EOTE system design. The present report presents the results of a test of fine positioning control carried out using two different manipulator systems varying widely in manipulator configuration and control systems. Fine position control is viewed as representing a fundamental requirement placed on manipulator control. The relationship of position control to more complex tasks which directly represent on-orbit servicing operations are also presented.

2.0 MANIPULATOR SYSTEM EVALUATION METHODOLOGY

2.1 General Evaluation Approach

The over-all evaluation sequence is designed to initialize testing of a particular manipulator system with tests which are common to many servicing tasks. The task sequence proceeds from general capability tests such as fine positioning to specific tests such as module removal and replacement. To some extent, the test are also ordered in terms of increasing difficulty (i.e. number of tip degrees of freedom which must be controlled, accuracy requirements, etc.) The general strategy is to accept, modify, or reject manipulator systems based on system performance during precedent tests before proceeding to later tests. A particular system will thus have demonstrated capability on earlier tests in terms of performance relative to other systems or to absolute standards before proceeding to later tests.

The tests which measure various aspects of man/system performance in manipulator control are listed below:

- Minimum position change - The operator attempts to carry out fine positioning changes with the manipulator arm. The end effector holds a stylus and the task requires only position control of the tip of the stylus. The movements executed vary in terms of distance moved and terminal accuracy required.
- Dexterity - The operator attempts to remove cylindrical pegs from one task board and to insert them in holes in a second board. This task requires precise positioning and orientation and should prove more difficult than the minimum position change test. The peg/hole relationships vary in terms of movement distance, terminal accuracy, and peg/wall clearance. The dexterity test requires accurate positioning in up to five degrees of freedom while three degrees must be controlled for minimum position change.
- Tip position - The operator attempts to achieve a commanded tip position and to hold that position for a specified period of time. Tip position corresponds to a position step input with the operator closing the loop.

- Tip orientation - The operator attempts to achieve a commanded tip orientation and to hold that orientation for a specified period of time. Tip orientation is an attitude version of tip position.

- Force-torque application - The operator attempts to move a spring centered device by applying force with the manipulator arm. Using a known spring constant permits measurement of the operator's ability to apply a graded force by measuring position. The direction of motion may be varied.

  Fastener connect/disconnect - The operator uses the manipulator and end effector to open and close various fasteners typical of those used on spacecraft.

- Module removal/replacement - The operator attempts to remove modules of various sizes and configurations from a rack and to replace the module. The modules will typify those to be employed in serviceable satellites.

- Antenna deployment - The operator attempts to extend an omni-antenna without deflecting its base. This test requires application of a graded force over a distance without application of force orthogonal to the vector desired.

The tests described above will be carried out with a variety of manipulator/end effector/controller combinations. Combinations which will be tested include:

RAM	Terminal pointer controller
RAM	MIT Controller
RAM	Terminal pointer controller, with joint friction
RAM	Two stick controller concept
RAM	Direct joint control
ESAM	Replica controller
ESAM	Analog joystick controller
ESAM	Terminal pointer controller

The application of eight test types to eight manipulator combinations would appear to require the conduct of 64 separate test series. Since various parameters such as gains, controller/joint relationships, control/display ratios must also be varied within a particular manipulator configuration, the total number of tests required becomes impractical.

The rationale for limiting the total test effort requires that careful consideration be given to system parameters prior to testing and that the tests are arranged and applied to a manipulator system in a fixed and logical order. The rationale is that tests should be arranged in order of increasing difficulty and of increasing specificity with respect to satellite servicing operations. A manipulator system which cannot "pass" an earlier test would not be subjected to a later test unless it had been suitably modified. The process of developing suitable system parameters will interact with the testing process. Furthermore, a manipulator system which shows poor performance on earlier tests can be dropped from further testing if this is appropriate.

The order of tests which will meet this rationale is based on the assumption that a manipulator system must be amenable to accurate tip positioning, tip pointing, and application of suitable force in an appropriate direction. These factors could be called positioning, orienting, and forcing. The order of tests being employed in the manipulator evaluation effort is shown in Figure 2-1.

The initial step in the proposed effort is the specification of a manipulator system which comprises an arm, an end effector, a controller, a set of control laws, and a visual system. The total system also includes an operator who is suitably trained. Given these system elements, system integration will involve the selection of a set of system parameter values such as control gains, video levels, etc. These characteristics of the manipulator system have been enumerated by Malone et.al. (1974). The system parameters will generally be controlled at fixed levels during a particular test and will be changed only between tests. Generally, the independent variables of a test will be the task parameters such as task placement with respect to the manipulator base, motion direction, etc.

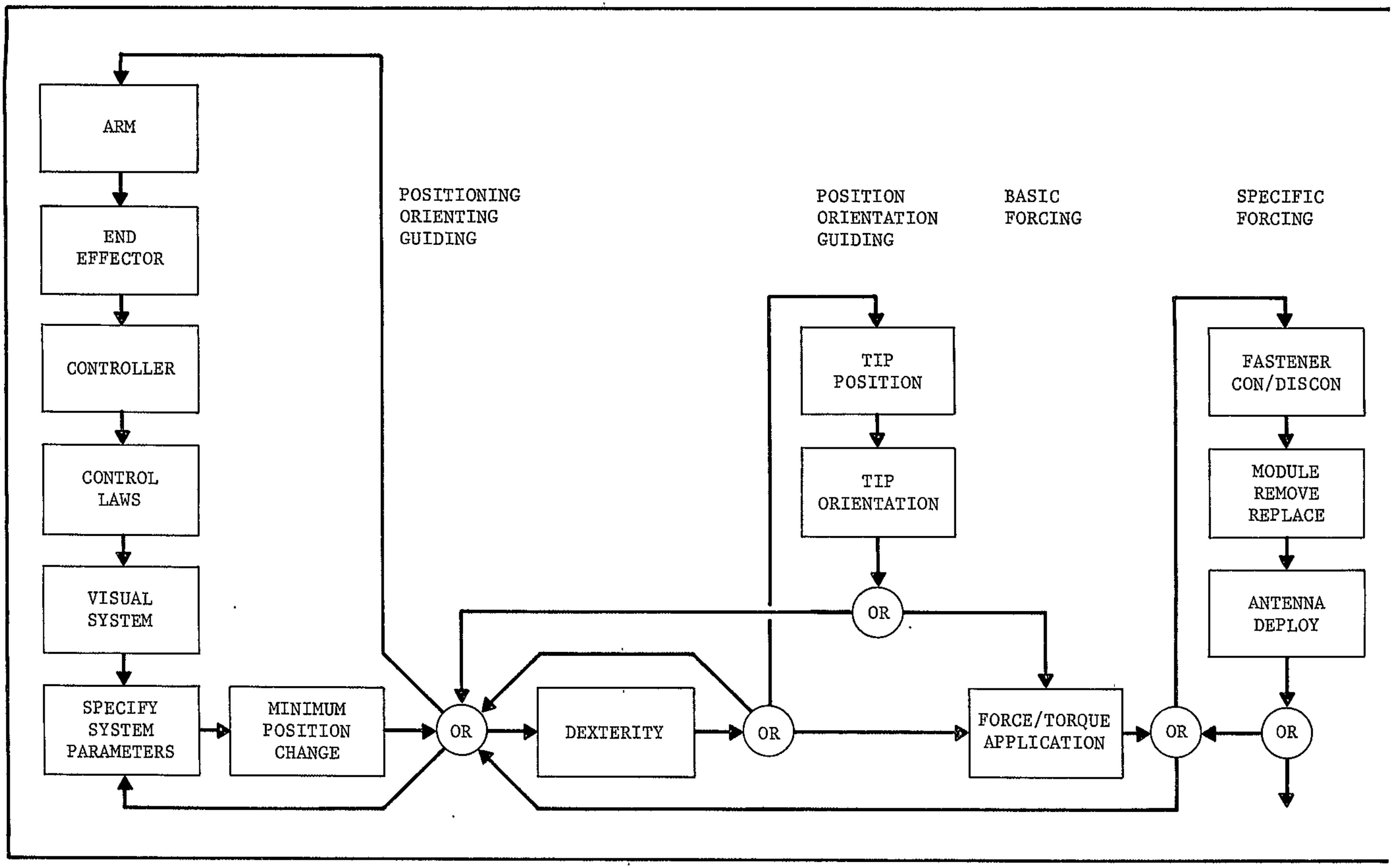

Figure 2-1. FLOW OF MANIPULATOR SYSTEM TESTS

According to the procedure shown in Figure 2-1, the initial test to be carried out is minimum position change. This tests the system's capability for fine tip positioning and yields movement time as a function of movement distance, terminal accuracy, and movement direction. Control of end effector grasping is not required. Test completion yields a sample of observed movement times for trials performed by a group of trained subjects. The analytical methods for comparing system performance on the test will be discussed later. It will be assumed that a figure of merit based on movement completion time can be derived and compared with an absolute standard or with the corresponding statistic for an alternative system.

Based on this comparison, three courses of action are shown in Figure 2-1. In one case, the performance of the system may be judged unacceptable. This path leads back to the system specification phase since qualitative changes are presumably required. In the second case, observations made during the test, the opinion of the operators, or engineering judgment may suggest that a change in the system parameters would improve performance. The change can be made and a portion of the minimum position test repeated to verify results. This loop may be repeated any number of times based on the test outcomes. The third possibility is that system performance on the minimum position change task is judged adequate. This branch leads to conduct of the dexterity test.

The dexterity test adds to task difficulty in at least three ways. In the minimum position test, the stylus held by the end effector has small area compared to the target area within which it must be placed. The peg insertion task used for the dexterity test introduces the factor of peg/hole clearance. The peg cross-sectional area is a large fraction of the hole cross section. Assuming a reasonably stable control loop, the time to complete peg insertion may depend on the parameters of the visual system as much as on manipulator dynamics.

A second factor is that the dexterity test requires control of more degrees of freedom than does the minimum position change test. The latter permits yaw to compensate for lateral position error, etc. Only the position of the stylus tip is critical. The dexterity test, however, requires control and accurate positioning in at least five degrees of freedom. If square pegs are employed, or if a cylindrical peg with a protruberance is used, all six degrees of freedom will be involved.

Finally, the dexterity test requires utilization of the end effector. The test will require transfer of four pegs so the grasping and releasing of the end effector will impact task completion time. In the minimum position change test, by comparison, no end effector action is required.

Completion of the dexterity test for a particular manipulator system would result in a decision whether to modify the system, or to conduct additional tests of position and orientation control. The latter course of action branches to the tip position and tip orientation tests. Note that these tests are not on the "main line" of Figure 2-1. They are akin to diagnosis of problems encountered during the minimum position change and dexterity tests. The basic nature of tip position and tip orientation involve closed-loop step responses with the operator in the loop. The tip position test particularly involves larger movement amplitudes than does minimum position change. Tip position and orientation tests would be applied to systems which show a tendency to overshoot or to go unstable. While complex effects of control system design on the operator are not likely to be encountered with small manipulators and simple position or rate controllers, it has been noted in the literature that the adaptive nature of the man's control response permits him to stabilize unstable systems and sometimes to destabilize stable systems.

Accordingly tip position and orientation tests are included as contingency tests for any stability problems which might arise. Such testing would be accompanied by fairly complete strip chart recording of controller command and joint feedback potentiometer voltages, to permit exhaustive and detailed analysis of responses.

Assuming that the results of both the minimum position change and dexterity tests for a particular manipulator system are favorable, the rationale for testing would then proceed to tests of basic capabilities for forcing in a desired direction. The system would be assumed to have "passed" tests relating to position, orientation, and path control.

The force/torque test described previously is designed to measure a system's capability for producing a graded or quantitatively appropriate force in a desired direction. The exact mechanism to be employed for the test will be specified and the test procedure will be developed during the proposed effort. The present plan is to utilize a spring-centered task module, force and position then being linearly related. The drawback to this scheme is that visual position feedback would give the operator a cue to his current force application and this cue would be lacking in the real world. Such a test might fail to adequately address the need for force feedback systems in situations where visual feedback relating to force is not available. Force sensors would be required as a part of the test hardware if this factor of the task were judged to be significant.

As in the case of position and orientation tests, the force/torque test could result in a decision to continue in the test sequence or to recycle to evaluate system and/or parameter changes. If the system performance in basic forcing in several directions were acceptable, the remaining tests shown in Figure 2-1 would measure performance in tasks specific to satellite servicing operations. The complete test sequence therefore will measure positioning, orienting, and forcing capability of various manipulator systems. These basic factors in manipulator system performance will be assessed via general or basic tests. A system may be modified and retested at any point in the process or a particular system concept may be rejected depending on its performance relative to an absolute standard or to other systems being tested. Systems which "pass" the basic positioning, or forcing tests will be tested on tasks specific to satellite servicing operations. Because a particular system may be rejected or modified during the process, the total amount of testing is reduced and the majority of testing effort which is performed is devoted to systems which have shown some degree of capability by "passing" previous tests.

Because common tasks will be performed by a common set of operators, the experimental design will permit direct quantitative comparison of these configurations in terms of system performance measured by task completion time and accuracy. In addition to this comparison, data will be available on optimization through camera placement, lighting, control gains, control/display ratios, and operator procedures. Further, the manipulator configurations to be evaluated represent classes of systems (i.e. number of joints, movement limits per joint, maximum rates, controller type, etc.). The evaluation in terms of system performance measures will, therefore, be generalizable to classes of systems and design criteria and requirements may then be stated with respect to general system design parameters. The procedure thus provides both specific evaluation in terms of optimum controller type, number of joints, control gains, etc.

An important feature of the proposed tests is that they are elementary operations in satellite servicing functions. A specific satellite servicing problem might involve opening a hatch secured by fasteners, removing several printed circuit boards, replacing them, and securing the hatch. This total maneuver may be analyzed into a positioning movement and fastener disconnecting movement for each latch, fine positioning for card removal and replacement, etc. The data collected on the elementary operations, each represented by a particular test will determine the probability distribution function for completion time of the operation. Using an operational sequence diagram which decomposes servicing into elementary operations together with the empirical distributions, a stochastic model may be developed to predict total task time and task success probability. Such an approach will yield quantitative prediction of system/operator performance for any servicing situation which may be analyzed into component elementary operations.

2.2 Figures of Merit for System Comparisons

Measures of performance of various tasks by a manipulator system will include:

- Response accuracy
- Response time
- Resource consumption

Response Accuracy and Response Time - Response accuracy refers to terminal error or tolerance in positioning and orienting or to magnitude and direction errors in force application. Most of the tests to be employed in the proposed effort have controlled accuracy-the system must achieve a designed accuracy for the trial to be successfully completed. Response time refers to the time to complete a required movement or other manipulator action.

Tasks vary according to whether time and accuracy are dependent measures or independent variables. Forced pace tasks allow a fixed response interval and yield accuracy measures. Alternatively, the required accuracy can be fixed and time recorded as a dependent measure. In simple step function or acquisition tracking, accuracy may be limited only by display resolution given sufficient time and a seasonably stable control loop. The latter case typifies many of the manipulator tasks to be employed here. These tasks involve, for example, moving a manipulator tip to a desired position. If the task involved tracking a moving target having significant derivatives of position in its course, accuracy measures would be more appropriate, as an example, moving a manipulator tip to a desired position. If the task involved tracking a moving target having significant derivatives of position in its course, accuracy measures would be more appropriate, for example; RMS error. Such cases are obtained in mobility system control. Manipulator control, however, is primarily a question of position requirements. The rate of motion being important in terms of time to complete the task but not being an input which the system must match. The amount of time required to perform a task of specified accuracy is, therefore, the dependent measure of primary interest as regards manipulator system dexterity.

Resource Consumption - Resource consumption measures would include at least electric power consumption and operator workload. Power consumption measures appear to be warranted later in the teleoperator technology program. Obviously, the operating power profile for a system must be known for orbital operations and total FFTO design. Power consumption, however, appears to be a tradeoff criterion to be used in selecting among systems which achieve adequate performance effectiveness rather than an effectiveness measure itself.

Figures of Merit

A measure of performance which simultaneously considers accuracy and response time is generated from a time-accuracy relationship proposed by Fitts and Posner (1967). This functional relationship is known as Fitt's Law and has been found to account for a variety of time-and-motion study results. As employed to date, Fitts's law has applied to hand motion time data. It has also been proposed, however, that the relationship may also hold for manipulator systems and, if so, may provide a measure for comparing diverse systems and permit prediction of movement times for tasks other than those studied in the laboratory.

Fitt's initially noted that hand movement time is not closely related to movement distance if the final accuracy of the movement is not controlled. Large amplitude movements may be made in about the same amount of time as small movements if the terminal accuracy required is varied in proportion to the movement amplitude. Movement time then depends explicitly on the ratio of amplitude to tolerance. This ratio can be computed from the physical dimensions of a movement task having a starting position and a target of fixed size.

Fitts studied the relationship between response time and the amplitude to tolerance ratio via an experimental task in which the subject held a stylus and moved it from an initial contact to a target contact. The center-to-center distance between the contacts and the diameter of the target contact could be varied independently. The result was that mean movement time was a logarithmic function of the ratio of amplitude to tolerance.

Fitts interpreted the logarithmic relationship in terms of an information processing limit on the nervous system. The amplitude to tolerance ratio may be thought of as an information theory measure where the amplitude is considered to be the message. This corresponds to an observer attempting to discover the distance between the contacts from the pointing movements made by the subject. The initial uncertainty depends on the range of possible amplitudes. Following the movement, this uncertainty is reduced. There remains some residual uncertainty due to the tolerance of terminal accuracy.

In this application of information theory, the possible center-to-center distances form the message set (a continuous one) and the message is the particular distance involved. The channel is the subject performing the pointing task, and the receiver is a hypothetical observer attempting to determine the center-to-center distance. In such a case, the uncertainty reduced by the movement would be the initial uncertainty minus the residual uncertainty in bits or:

$$u = \log_2\left[\frac{2A}{W}\right] \qquad (2\text{-}1)$$

where
u = information transmitted by the movement
A = movement amplitude
W = diameter of target contact

Fitts termed the information quantity in eq. 2-1 the index of difficulty since it measures the relative accuracy required by a particular movement and also influences the mean time necessary to complete the movement. The empirical relationship between mean response time and index of difficulty determined by Fitts was:

$$T = a + b \cdot ID \qquad (2\text{-}2)$$

where
a = intercept parameter (sec)
b = slope parameter (sec./bit)
ID = index of difficulty

The empirical values of <u>a</u> and <u>b</u> were determined by Fitts by collecting response time data for a variety of movements differing in amplitude and tolerance and plotting mean movement time against index of difficulty. This plot was found to be linear and the inverse of the slope was interpreted by Fitts as a measure of the information transmission rate of the motor system.

For discrete stylus movements, Fitts found b to be approximately .074 sec per additional bit of information generated by the movement required. This corresponds to an information rate approximately 13.5 bits per second. This value would be expected to approximate the upper limit or channel capacity of the perceptual motor system since only simple hand movements are required.

Where direct hand movements are involved, Fitts's law has been found to generalize to a wide range of movement times including those involved in operating industrial equipment. The question which has been raised in connection with manipulator system evaluation involves the extent to which the movement time-index of difficulty relationship describes manipulator system positioning movements. If a constant limit on the information processing rate characterized a particular manipulator system, this would serve as a general figure of merit in comparative evaluation of systems and would also permit prediction of the time required to complete any movement with a particular manipulator system based on the index of difficulty of the movement and the information transmission rate of the manipulator system.

If a task analogous to that used by Fitts were performed using a manipulator system, a lower processing rate would be expected due to the dynamics of the system. An ideal manipulator should achieve a processing rate which is a substantial fraction of the 13.5 bits per second available with the hand. Two questions arise in the application of these concepts to manipulator system evaluation. These involve the degree to which Fitt's law describes manipulator performance and the possible limitations of processing rate imposed by the manipulator dynamics.

There is reason to expect that a Fitt's law form of expression will apply to manipulator task times. Craik's (1947) theory of the human operator in step function tracking with simple dynamics suggests that the operator acts like an intermittent data sampling system. Error nulling movements or "ballistic movements" are made at a rate of approximately 2 per second. These ballistic movements are open loop during their execution corresponding to the refractory period characteristic of the nervous system. Craik found that each ballistic movement tends to reduce the remaining error by a constant proportion as high as .90 for simple control systems. If these relationships apply generally to the human operator during step function tracking, they imply a relationship having the form of Fitts's law. Let:

A = amplitude of required movement (initial error)
W = terminal tolerance
P = error reduction parameter
k = constant time for one ballistic movement
Di = remaining error after i ballistic movements
n = number of ballistic movements required to null error.
Do = initial distance
a = intercept
T = total movement time
6 = slope

Then:

$$Do = A \quad (2\text{-}3)$$

$$Di = A(1-p)^{i} \quad (2\text{-}4)$$

The total movement is terminated after n ballistic movements if $D_n < \frac{W}{2}$

Substituting:

$$A(1-p)^{n} = \frac{W}{2} \quad (2\text{-}5)$$

Taking logarithms:

$$n \log (1-p)^{-1} + \log A = \log \left(\frac{W}{2}\right) \quad (2\text{-}6)$$

Rearranging:

$$n = [-\log (1-p)^{-1}] \log \left(\frac{2A}{W}\right) \quad (2\text{-}7)$$

Assuming that each ballistic movement requires k seconds:

$$T = a + kn \quad (2\text{-}8)$$

Substituting:

$$T = a + k \left[-\log (1-p)^{-1} \quad \log \left(\frac{2A}{W}\right) \right] \qquad (2\text{-}9)$$

Therefore, Craik's data imply Fitt's law with:

$$b = k \cdot \left[-\log (1-p)^{-1} \right] \qquad (2\text{-}10)$$

For Craik's data, the approximate values of the parameters were found to be:

$$p = .90$$
$$k = .50 \text{ sec.}$$

Fig. 2-2 shows two relationships, the data on hand movements from Fitts (1967) and the implied function based on Craik's (1947) data. In both cases, the intercept a has been ignored. The function based on Craik's data was calculated by substituting the index of difficulty and the values of the parameters a and k in eq. (2-9). The slope implied by Craik's data is 6.64 bits/sec.-about half the rate achieved in Fitts's experiment. Presumably the difference is due to the introduction of control system dynamics in the Craik study as opposed to Fitts's task. The series of lines at the bottom right of Figure 2 shows the slopes corresponding to various values of the error reduction parameter p with k fixed at .5 sec. The bit rate for Craik's data may be expected to approximate an upper limit on the manipulator/operator information rate since these data were obtained for a simple one-dimension tracking task. This conclusion, however, conflicts with Vertut's (1973) data since a control system to hand tracking bit rate ratio of 2.0 was infered from the Craik and Fitts data. Vertut, however, obtained a minimum manipulator to hand ratio of 1.5. The problem may lie with the intercept parameter a. In the control system version of Fitt's law, the parameter presumably represents an irreducible minimum time possibly associated with overcoming static forces in the initiation of movement of the manipulator.

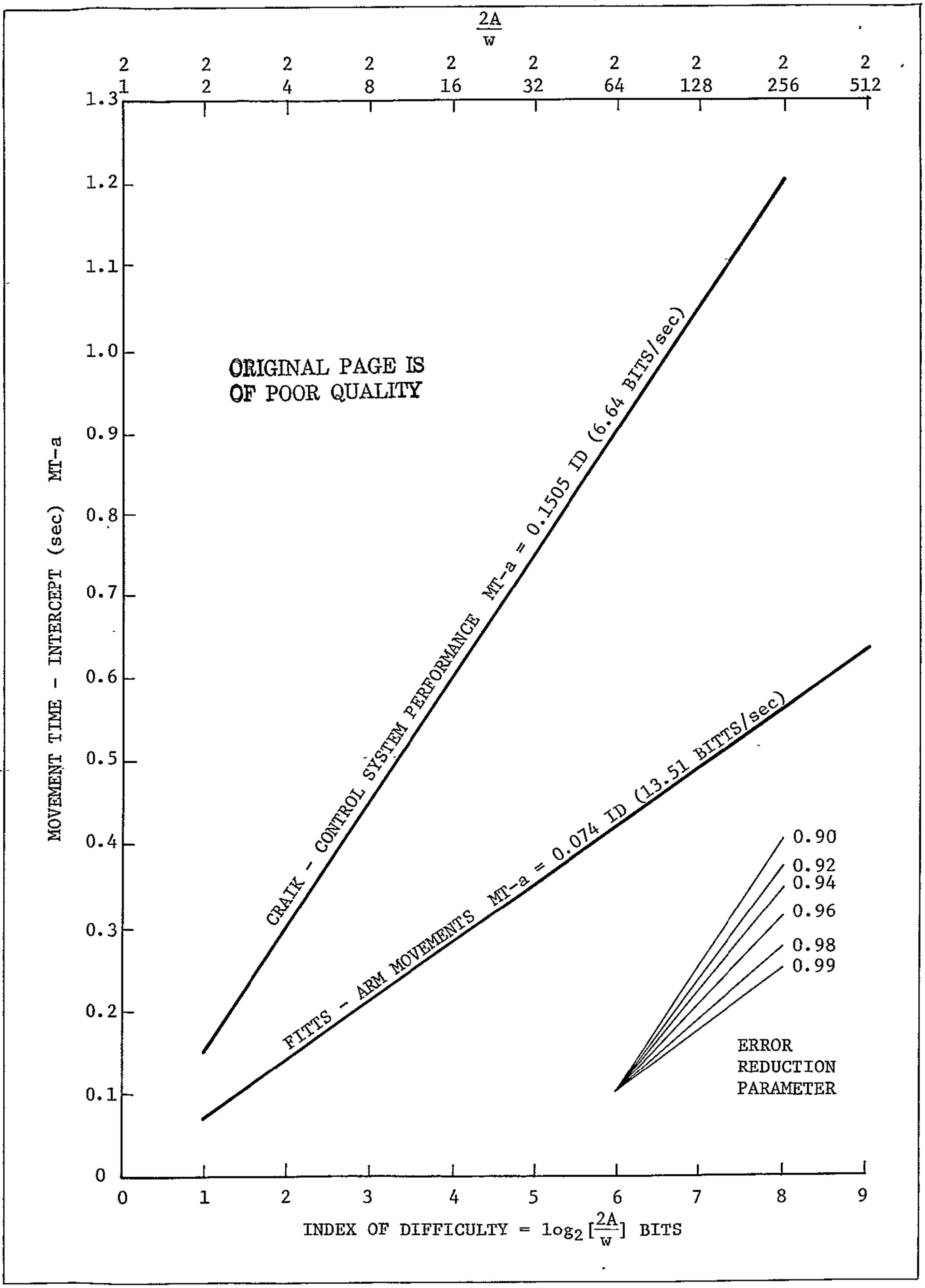

Figure 2-2. RELATIONSHIP BETWEEN MOVEMENT TIME AND INDEX OF DIFFICULTY

In Fitts's (1967) results, the least squares value of a was negative. The probable explanation is that in Fitts's experiment, a reaction time period preceded the movement time period. The reaction time contained a decision as to which of several targets was the correct one for that trial. Subjects were instructed not to move the stylus from the "home" contact until this decision was made. It seems likely that the negative intercept arose from this procedure. At any rate, the existence of intercepts for manipulator and hand times means that simple time ratios and processing rate ratios will not be identical. The relationships will depend on the numerical values of the intercept.

The Fitt's law approach in the current context appears to have the potential to generalize the results of particular tests. If Fitts's law is found to describe movement time, then the corresponding time for other movements not included in the initial test will be predictable based on the amplitude and tolerance required. In discussing the bit rate for simple tracking, the results of Vertut (1973) are relevant. Vertut tested a number of manipulator systems on several tasks and used as the dependent measure the ratio of the time to complete the task using the manipulator to the time required for direct completion by hand. This measure has the advantage of directness and face validity. It permits statements such as the fact that a particular manipulator requires ten times as much time as does the hand. This ratio also has an absolute interpretation since an ideal manipulator would presumably score unity. The Fitts law relationship, if found to describe manipulator performance would yield a more general measure via the ratio of information processing rates. By figure 2-2 it is evident that if two systems differ in terms of processing rate, the ratio of manipulator to hand time will vary with the index of difficulty. It will also depend on the intercepts or minimum movement times for the two systems.

The approach employed in the present evaluation effort was developed with the Fitts and Vertut measures taken into consideration. The minimum position change test was specifically designed to permit variation in index of difficulty and hand movement times were collected in addition to manipulator times to permit comparison of systems using both the Fitts and Vertut evaluation measures. The results of tests of two manipulator systems using the minimum position change task module are the subject of the present report.

3.0 MANIPULATOR SYSTEMS

The development of remote manipulator systems applicable to space missions is to be preceded by a series of comprehensive investigations into existing remote manipulator technology, operator control, and management of remote manipulator systems and RMS requirements and applications in space missions. NASA's RMS/EVA committee has assigned to Marshall Space Flight Center the responsibility for earth orbital teleoperator technology development and integration, especially as it applies to free flying systems (FFTS) and manipulator systems mounted internally to spacecraft.

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 experimental derived data on existing manipulator systems. The MSEL provides the necessary controlled environment for the study of each of the components of the manipulator system and the higher order interactions of the manipulator system components. As is the case in each of the 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 factors which may impact remotely manned missions.

The strategy for the conduct of manipulator system investigations was described in the General Evaluation Approach, Section 2.1.

The present test report describes the results of two test series carried out using the minimum position change task module. The manipulator systems tested were:

- MSFC Extendable Stiff Arm Manipulator (ESAM) with Analog/Joystick controller
- Rancho Los Amigos Anthropomorphic Manipulator (RAM) with resolved rate computer control and Terminal Pointer Controller (TPC)

3.1 ESAM-ANALOG/JOYSTICK SYSTEM

The ESAM is a non-anthropomorphic, five-degree-of-freedom manipulator representing the state-of-the-art achievement for general purpose remote manipulator units. The ESAM was designed and developed at the Marshall Space Flight Center and evaluated at the Manipulator Laboratories of MSFC.

The ESAM, as depicted in Figure 3.1, is basically a tubular, fixed member having a square cross section which provides support and storage for an extendable stiff member. The extendable member has a wrist assembly which provides roll and pitch positioning to 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 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 28 volt DC motor acting through a 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 660 degree envelopes in azimuth and 180 degrees in elevation.

The extendable member is a square cross sectional tube which telescopes within the fixed member. The extension is implemented by a 28 volt DC drive system. The extension range is 68 cm. (26.75 in.). The wrist pitch assembly at the end of the extendable member uses a 28 volt DC motor to drive the wrist 70 degrees in pitch. The final arm degree of freedom is wrist roll which has a range of 540 degrees and is driven by a 28 volt DC motor.

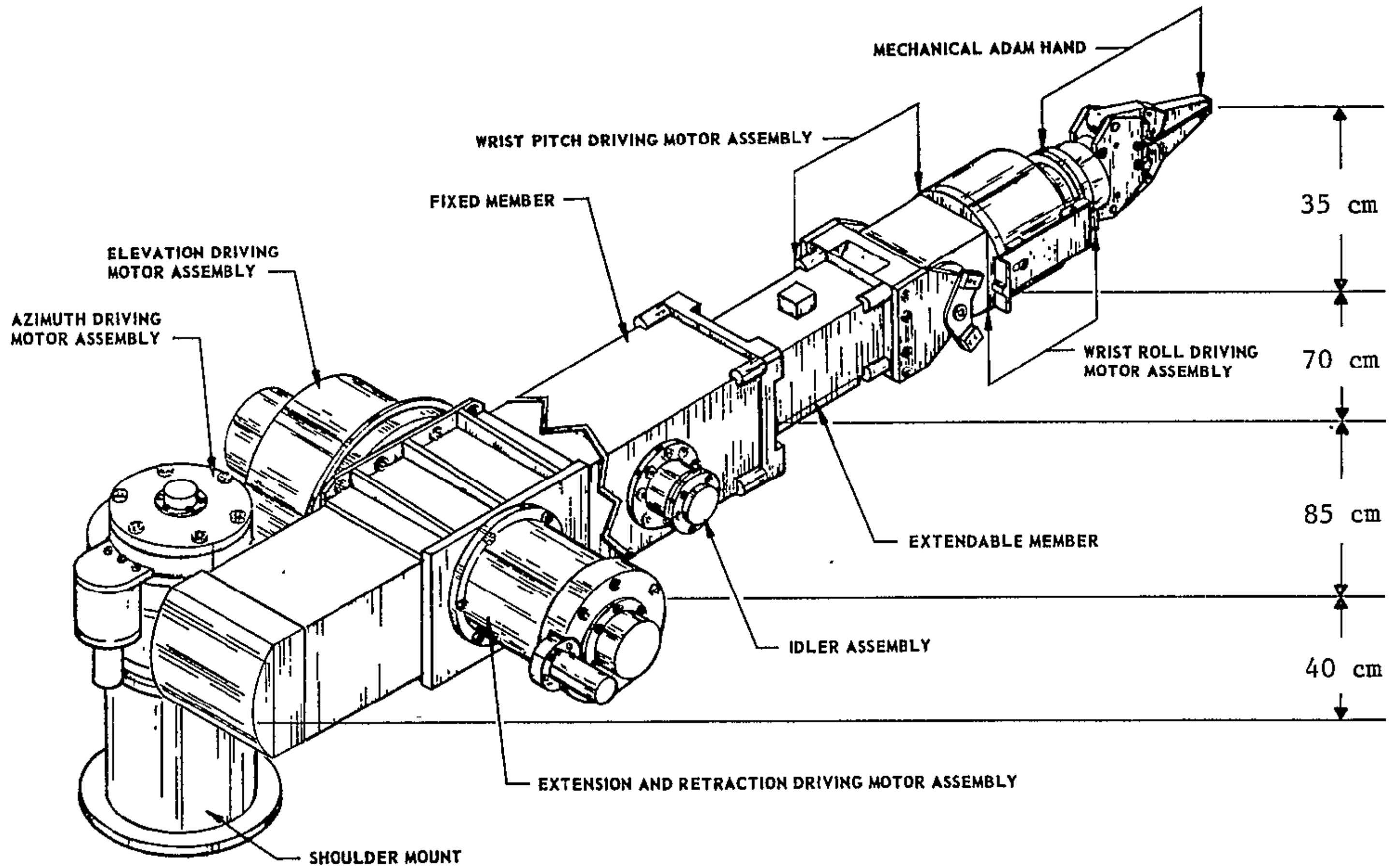

Figure 3-1. EXTENDABLE STIFF ARM MANIPULATOR SYSTEM (ESAM)

ESAM OPERATING CHARACTERISTICS

Table 3-1

	Max. Possible Displacement	Rate (Max)	Motor Drive	Gear Ratio
ARM				
Azimuth	660^{0}	27^{0}sec	41 kg-0.3M (120 oz-in)	480:1
Elevation	180^{0}	16^{0}sec	41 kg-0.31M (120 oz-in)	800:1
Extend/Retract	68 cm. (27 in.)	9.1 cm sec (3.5 in.sec)	18.2 kg-0.31M (40 oz-in)	120:1
WRIST				
Roll	540^{0}	30^{0}sec	5.1 kg-0.31M (15 oz-in)	480:1
Pitch	128^{0}	14^{0}sec	5.1 kg-0.31M (15 oz-in)	480:1

Controller

The controller concept used was that of analog/joystick control in which there is a geometric correspondance 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 combine the attributes of a position translation control system and a rate attitude control.

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 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. The controller command position also has X, Y, and Z coordinates and the two elements should be linearly related to produce wrist position as a linear function of controller position. The correspondence, however, is effected via azimuth, elevation, and extension degrees of freedom so that controller X, Y, and Z commands cannot be directly 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.

This transformation is accomplished by means of a four-bar linkage acting as a mechanical analog resolver. The four-bar linkage segments are scaled to the arm segments so that X, Y, and Z stick commands are resolved into azimuth, elevation, and extension values.

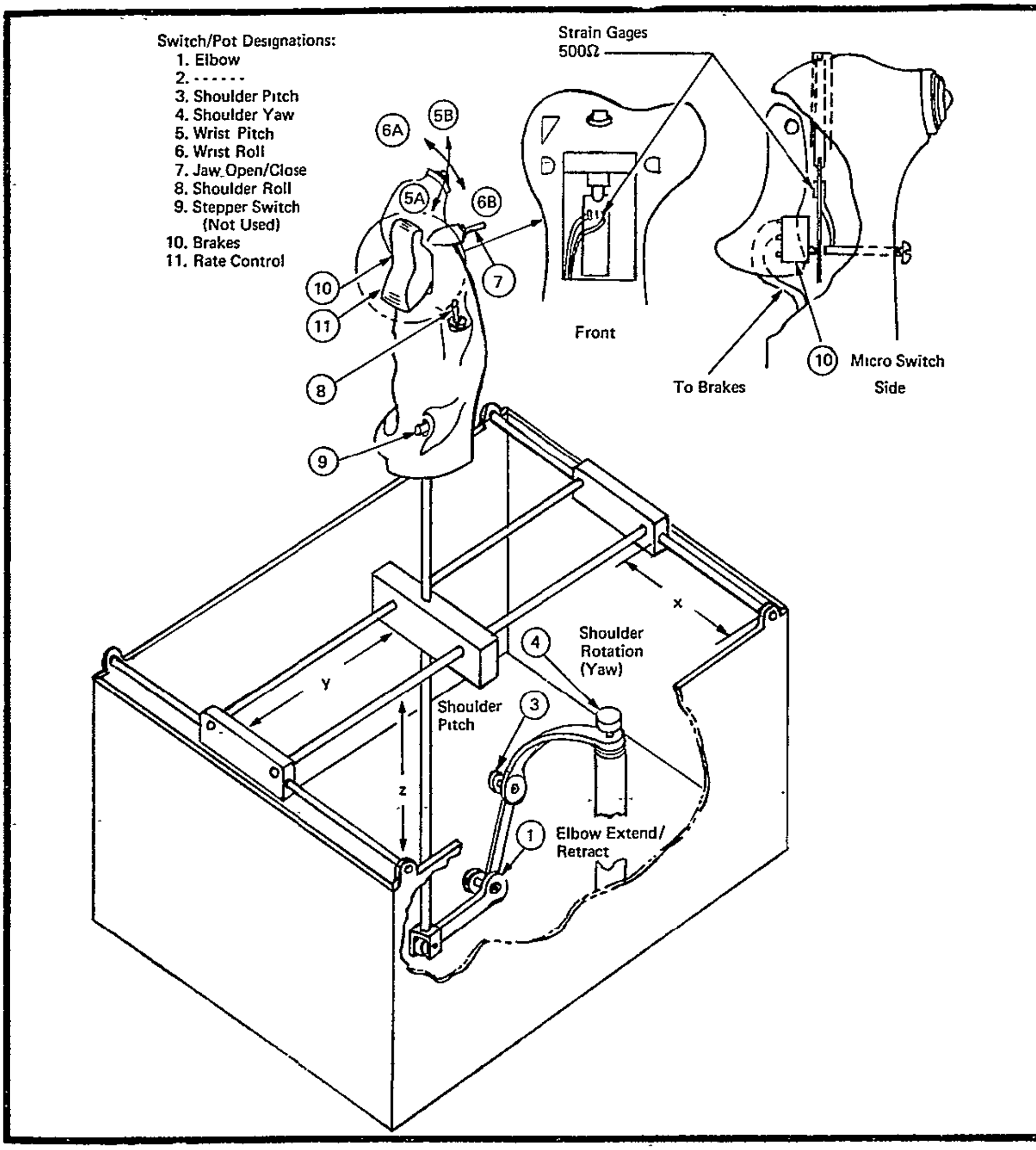

Figure 3-2. THE ANALOG/JOYSTICK CONTROLLER

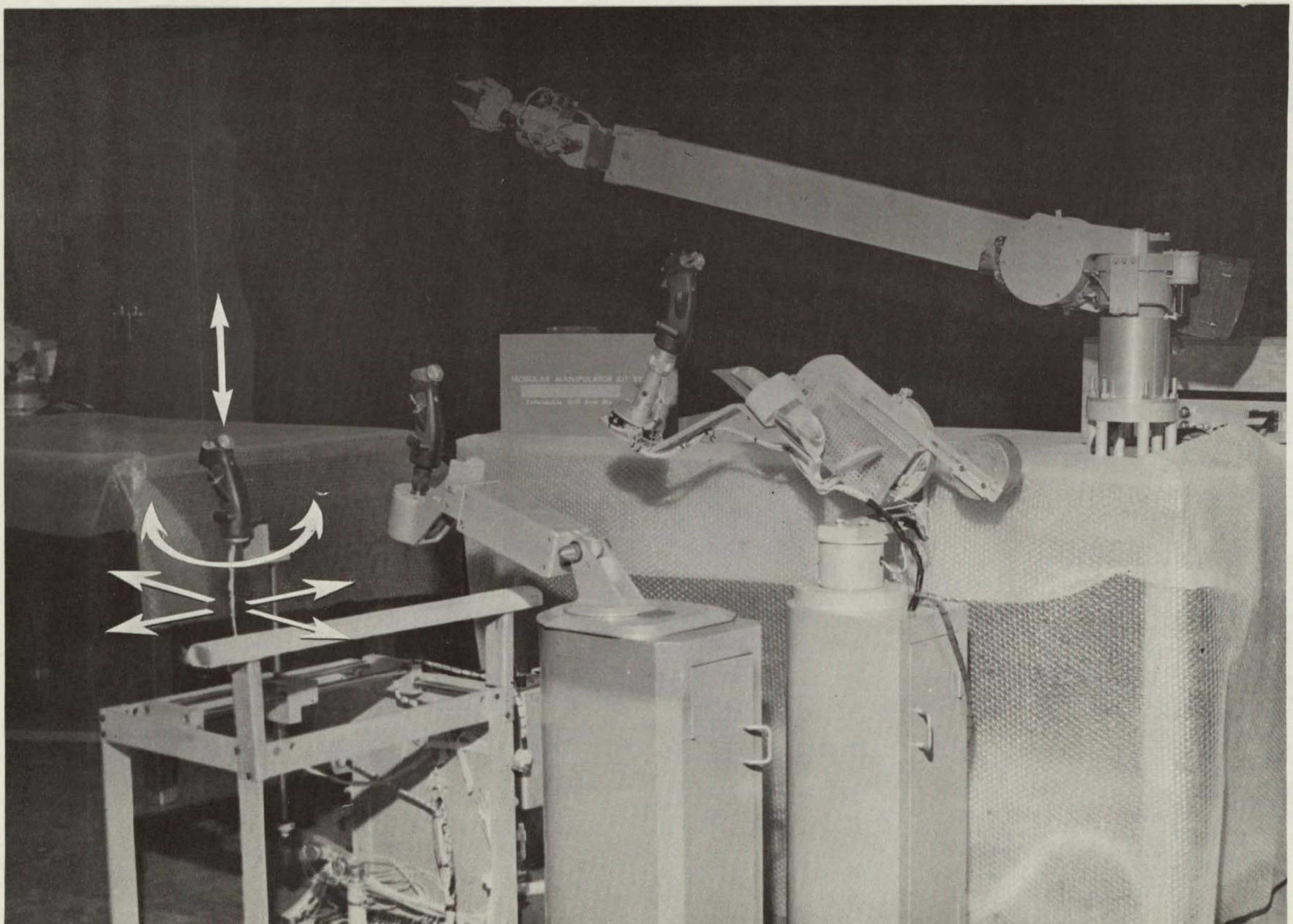

Figure 3-3. ANALOG/JOYSTICK WITH ESAM

Two control modes are used for the position and rate control systems. The analog controller employs a position command system with appropriate dead bands to yield accurate positioning of the end effecter. 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 direction to decrease the error to the 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 until a new error signal is supplied by changing the position of the control potentiometer. Three joints are controlled; azimuth, elevation, and extension. The wrist assembly joints (roll and pitch) are rate commanded. Direction of rotation is selected with the four-position switch on the handle. Rate is controlled by squeezing the trigger switch which is proportional to direct pressure. Releasing the trigger dynamically brakes the drive motor.

<u>Video System</u>

The video system used with the ESAM manipulator included the following components:

- Remote controlled TV cameras-Telemation, Inc., Model TVC-2100
- Telephoto zoom lens, 15-150 mm, F.1-2.8-Canon Camera Co., Inc-Model V10x15
- Remote controlled Pan & Tilt Units-Pelco, Inc., Model PT-550M
- Tripods-Hercules, Inc., Model 5450, for cameras.
- 8-inch, black & white TV Monitors-Conrac Model CNB8
- Camera Remote Control Panel-Cohu Electronic, Inc.

The display system used for this program consisted of two closed-circuit TV systems. All TV equipment was commercial "off the shelf" variety. The cameras were located orthogonally with respect to the task board and arm and their outputs were viewed by the subject at the operators console. Camera number one was a head-on view of the target and end effector and was viewed on the subject's left monitor. Camera number two was a view of the target and end effector from the right and was displayed on the right monitor.

3.2 RAM/TPC SYSTEM

Manipulator

The Rancho Anthropomorphic Manipulator is designed to correspond to the joint and joint-segment relationships of the human arm. The RAM has six degrees of freedom plus effector grasp. The six joints provide the following motions:

- Shoulder roll
- Shoulder flexion
- Elbow roll
- Elbow flexion
- Wrist roll
- Wrist flexion

The individual joints have rotation ranges of from 180 to 300 degrees. The joints are driven by 12 volt DC motors with gear reduction via worm and harmonic gears at the shoulder. The remaining joints use spiroid and planetary gear systems. Gear reduction at the joints ranges from 120:1 to 800:1. The forward reach of the RAM manipulator is 1.2 meter (3.94 ft.) at full extension. The RAM has a lifting capability of 25 lbs. (11.33 kg.) and the maximum joint torques vary from 5 ft. lbs.(.692 kg.M) at the wrist extention and forearm rotation to 25 ft. lbs.(3.458 kg.M) on all other joints.

Figure 3.4 shows the RAM. However, for this test only the single, left manipulator was utilized. The right manipulator was in a stowed position. Detailed information on this RAM system is contained in Rancho Los Amigos Hospital Final Project Report (1972).

Control System

The Terminal Pointer Controller (TPC) developed for MSFC was utilized with RAM for this test. The TPC uses a three degree-of-freedom position controller to orient the manipulator end effector, and then, using a two axis proportional rate control, translates in the direction to which the effector points.

The control concept involves orienting the controller in the selected axis. As a function of the coincidence of the controller axis and the natural movements of the operator's wrist in pitch, yaw, and roll, there should not be any necessity for complicated operator transformations. The output of the hand controller is scaled and interfaced with the digital computer through an analog to digital converter. The software program in the digital computer SEL-840 accepts the five hand controller outputs along with six feedback positions from the manipulator arm joints and forms a summation of vector cross products between an inertial frame and the end effector frame to provide closed loop tracking between hand controller and end effector. The output of this control portion of the software are rotational and translational rates of the end effector.

A Jacobian matrix is computed and the inverse taken, then multiplied by the five computed rate commands of the end effector, the results are six rate commands to the six joints of the manipulator arm. These are integrated in the computer and fed as position commands via D/A converters to the control servos that drive the six manipulator joints. Thus, five

TPC hand controller outputs are converted to six positional commands to the manipulator joints to affect rotation of the end effector corresponding to wrist rotation and translation corresponding to the thumb switch strain gage control. Cycle time for the computer is about 65 milliseconds.

The control servos that drive the manipulator arm joints are composed of power amplifiers, motors, gears, and potentiometers that measure joint position. Signals are fed back through a scaling amplifier for completion of the servoloop and for completion of the jacobian matrix and the control law in the computer.

The control system is illustrated in the functional flow diagram, Fig. 3-5 and the terminal pointer controller is shown in Figure 3-6.

Video System

The video system utilized with RAM/TPC testing was derived directly from the MSFC Visual System Laboratory. The system was composed of:

2 COHU 2000 TV Cameras
2 Conrac 7.75 inch monitors
2 Colortran Studio Lighting Units
2 Remote Units for Pan, Tilt, Zoom, and camera sensitivity control
1 21 inch General Electric Model

The system generated a 425 live signal at 4.5 MHz at the 7.75 inch Conrac Monitors. Signal to Noise Ratio was 32 db and the signal was the standard analog signal.

The two cameras were positioned orthogonally with respect to the target (Fig.3-7) with the camera normal to the task surface being elevated above the manipulator, and the other camera being approximately 90 degrees to the right. Figures 3-8 and 3-9 show the video system control and display panel, and the arms with the display.

Figure 3-4 shows the RAM, however during this test, only the single, left, manipulator was utilized. The right manipulator was in a stowed position. Detailed information on this RAM system is contained in Ref. 1 of Section 1 on this test report.

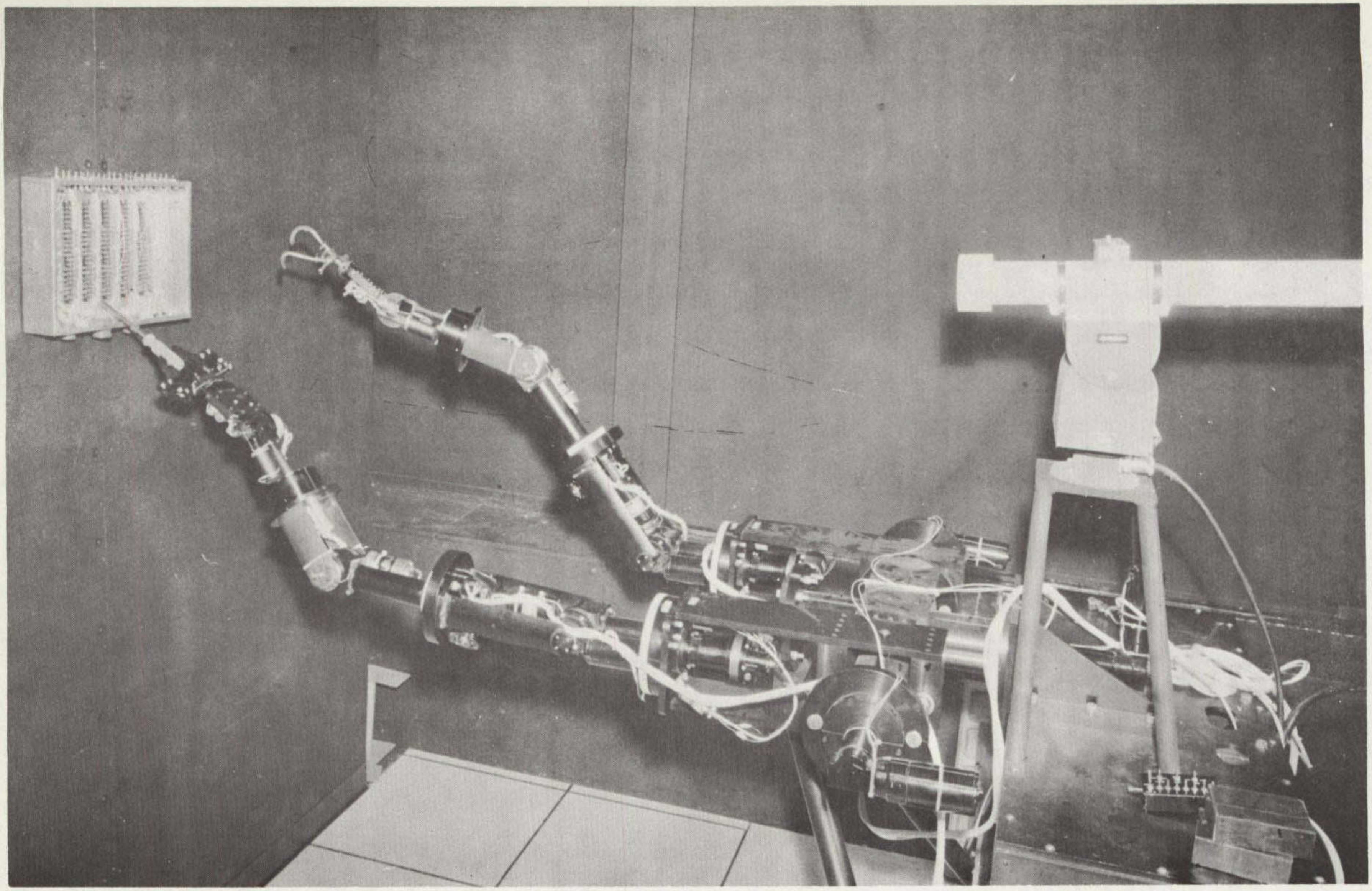

Figure 3-4. RAM/MSFC

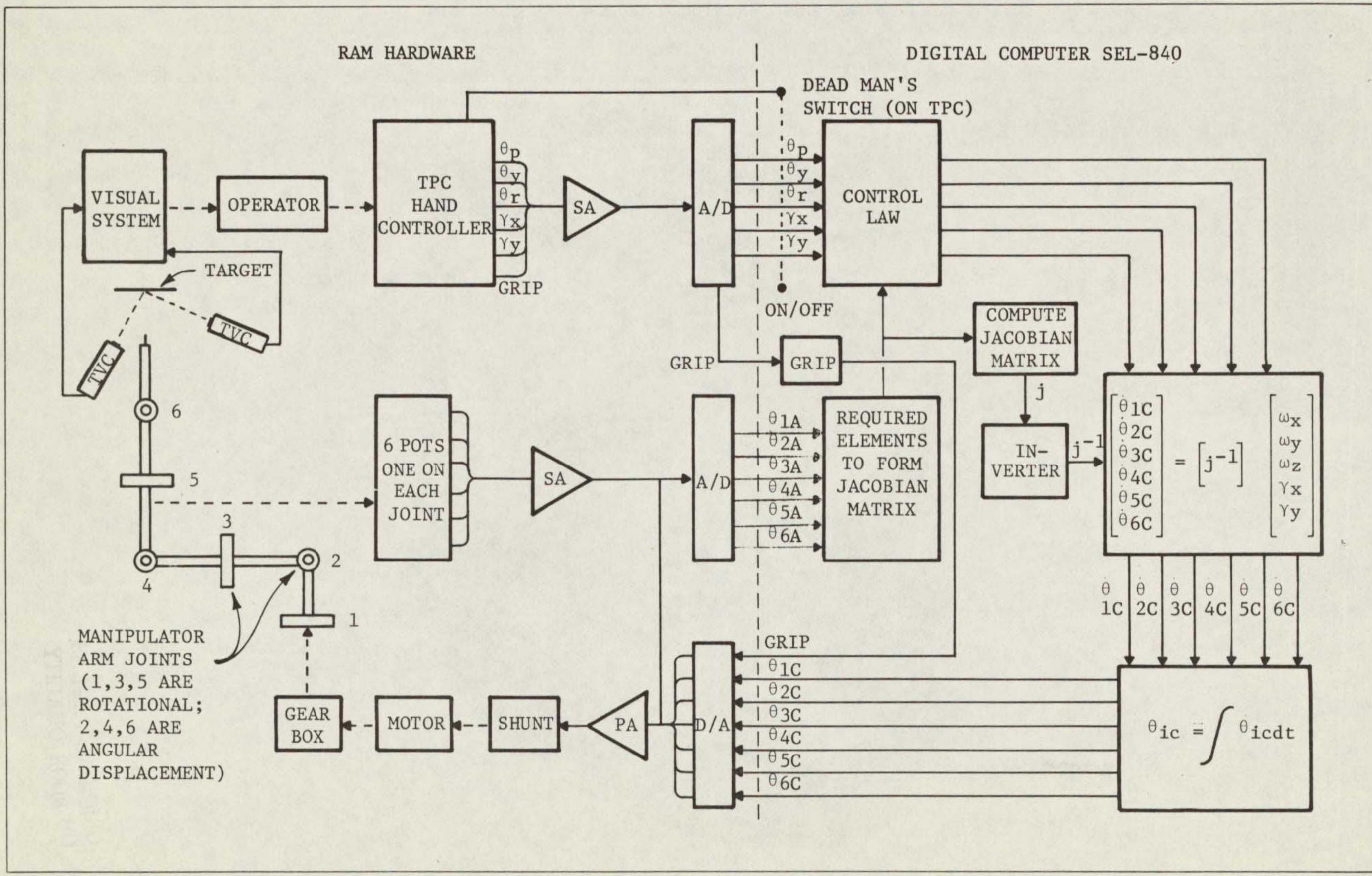

Figure 3-5. RANCHO ANTHROPOMORPHIC MANIPULATOR (RAM) SYSTEM

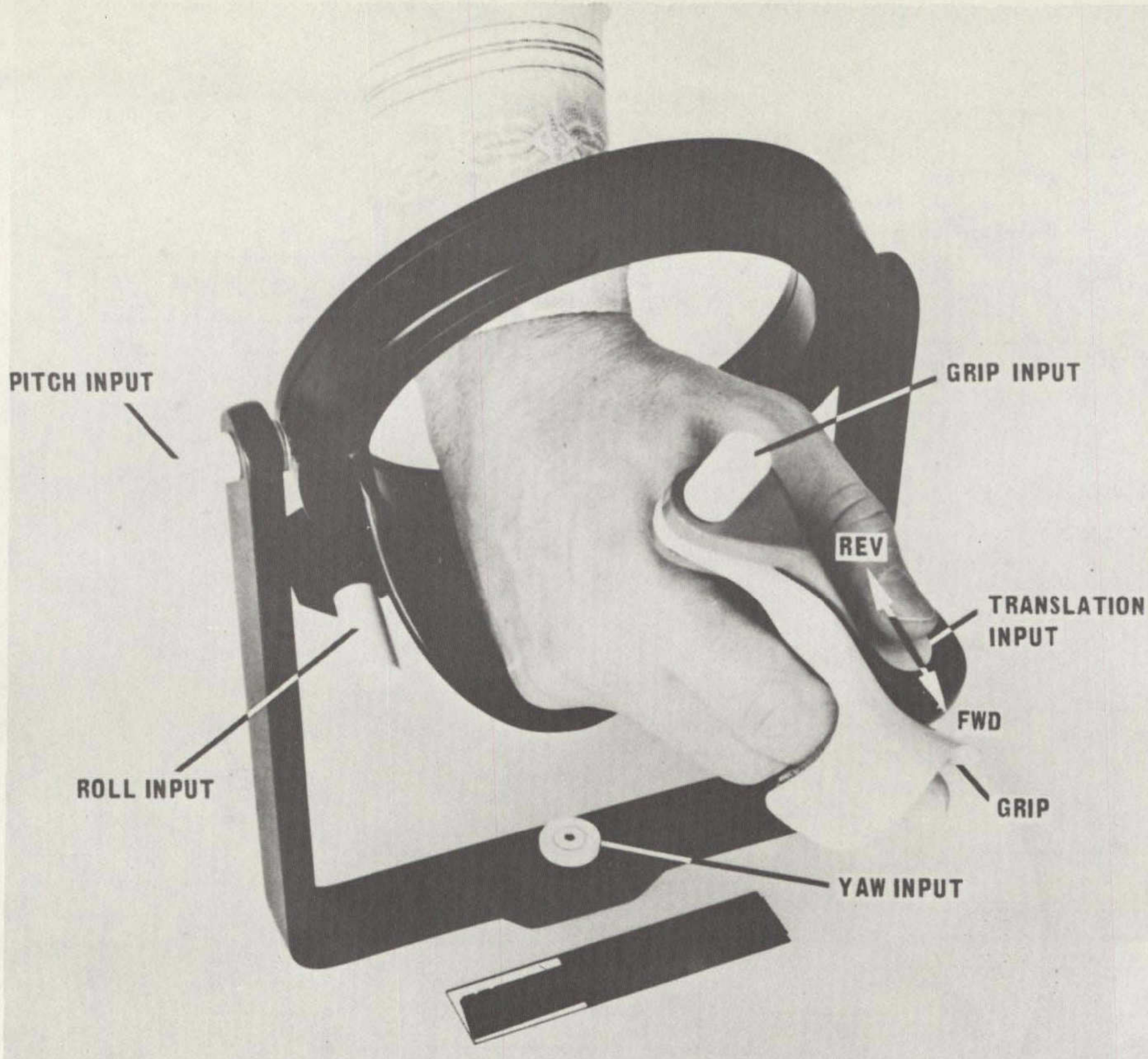

Figure 3-6. TERMINAL POINTER HAND CONTROLLER

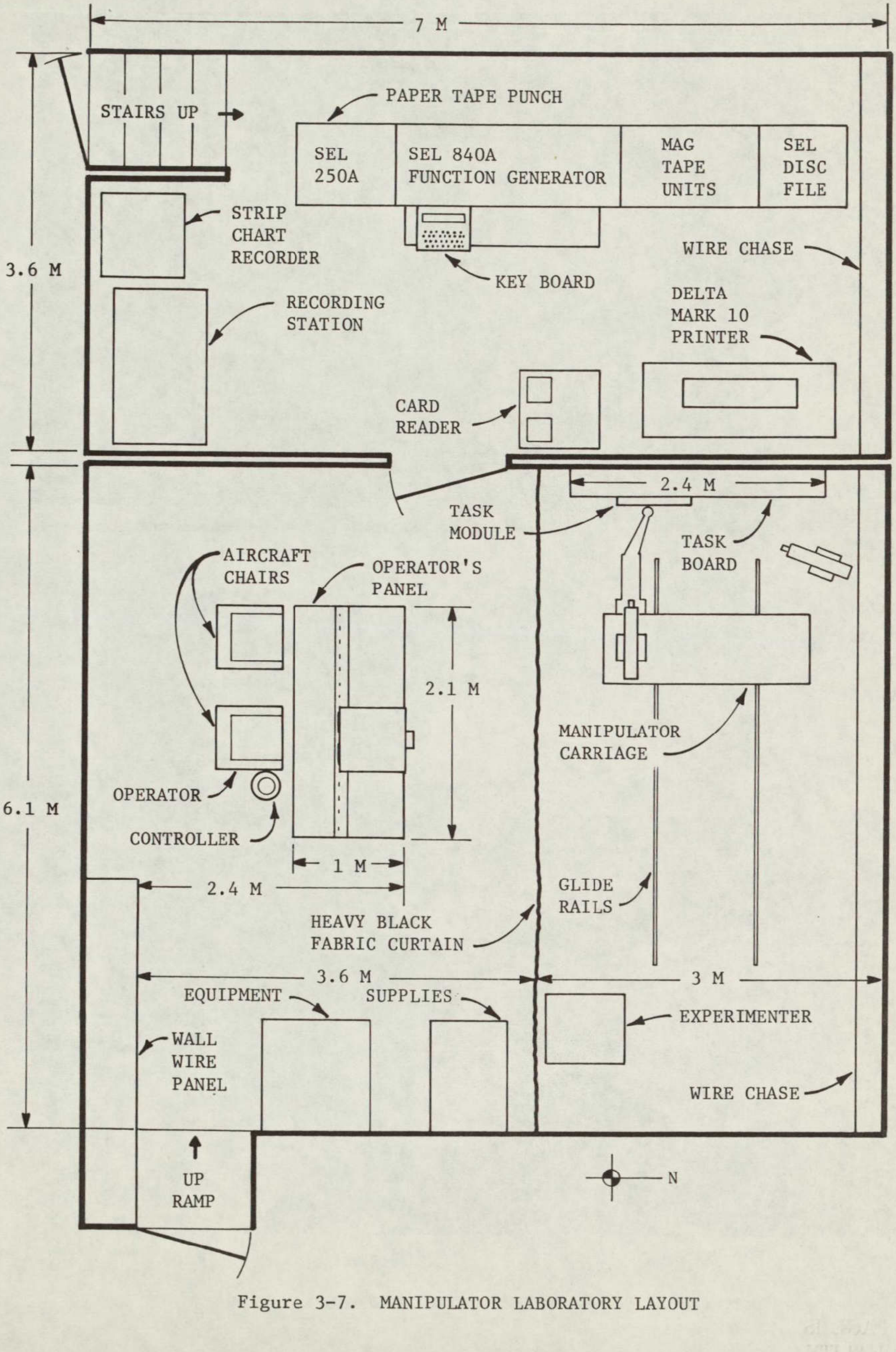

Figure 3-7. MANIPULATOR LABORATORY LAYOUT

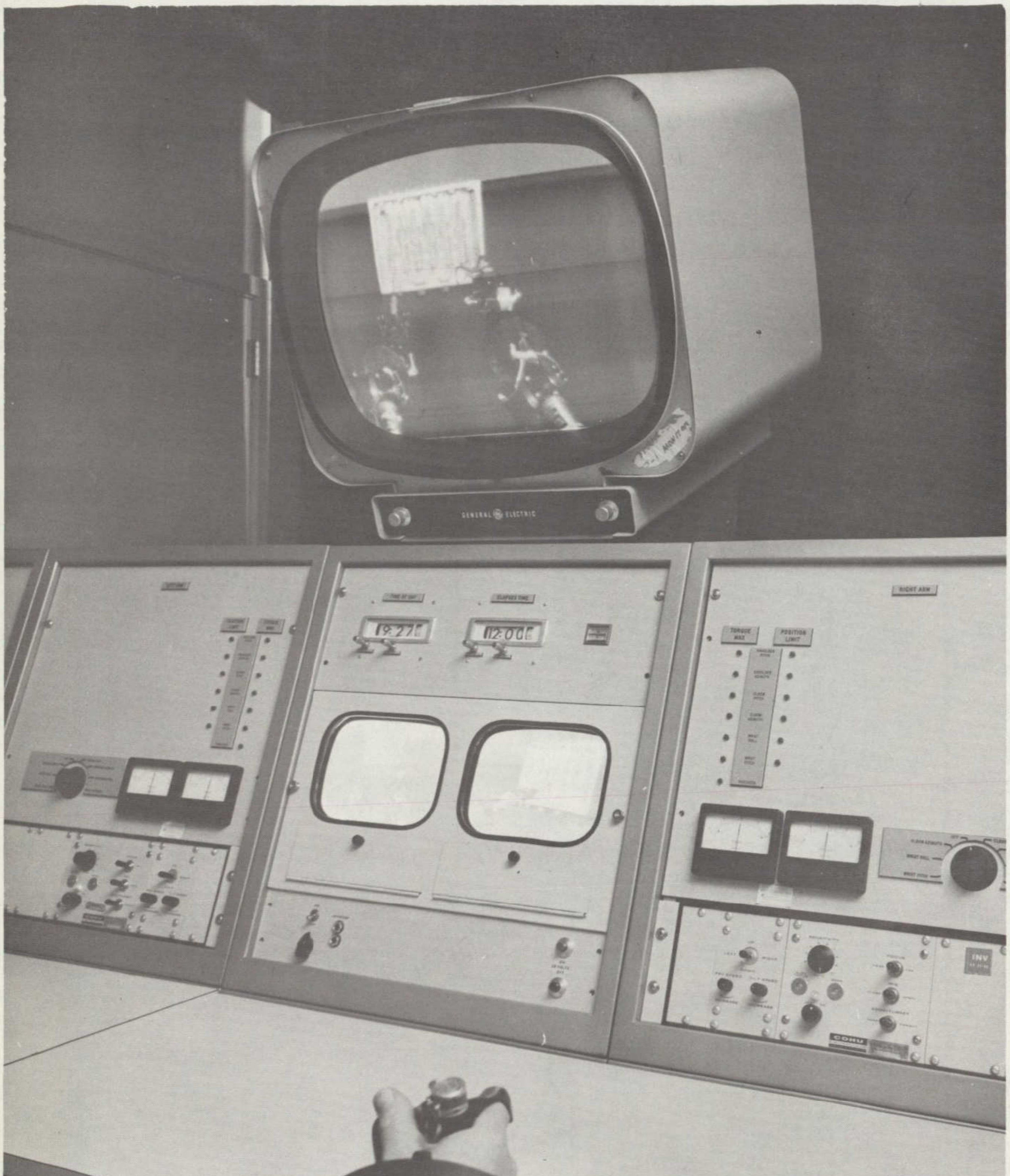

Figure 3-8. VIDEO SYSTEM CONTROL AND DISPLAY PANEL

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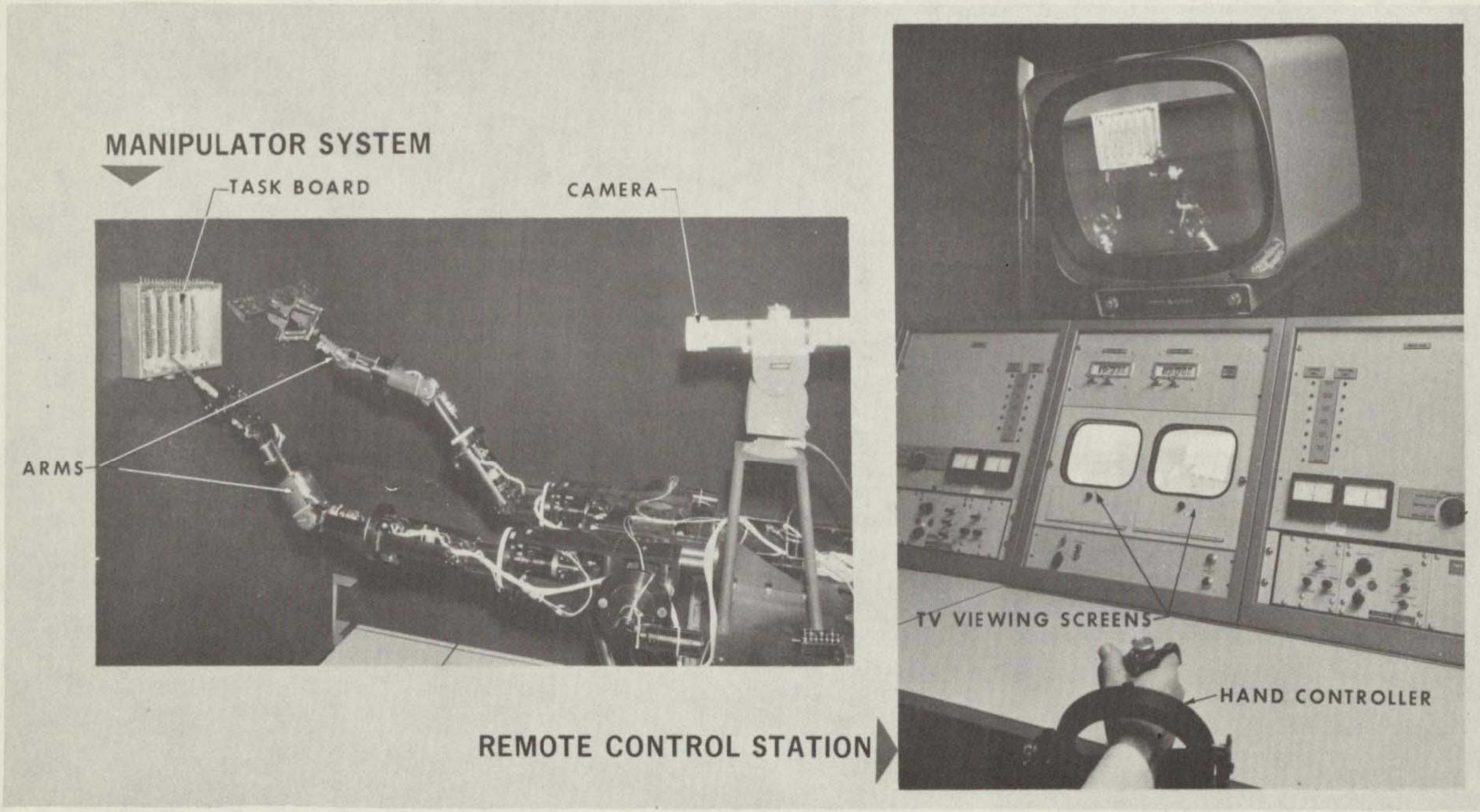


Figure 3-9. REMOTE ON-ORBIT SATELLITE SERVICING TECHNOLOGY

4.0 LABORATORY CONFIGURATION AND TEST PROCEDURE

4.1 Manipulator System Evaluation Laboratory

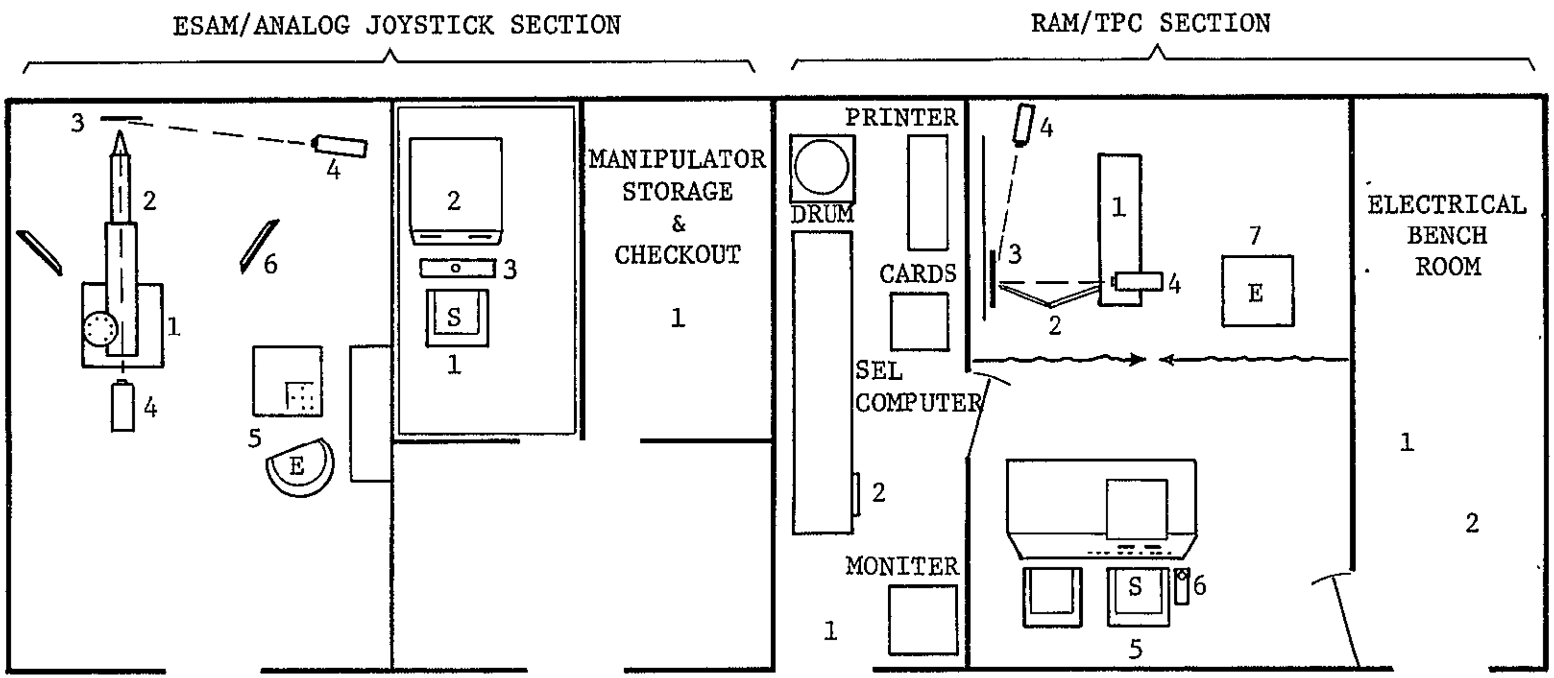
The MSFC Manipulator System Evaluation Laboratory is a general purpose facility providing the laboratory space, hardware, and integration necessary to collect quantitative data on manipulator system performance. The elements of the manipulator evaluation procedure being employed include:

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

The laboratory has appropriate environmental controls to limit the effect of extraneous variables. The several rooms used in this present test series are shown in Figure 4.1.

Prior to a test series, each manipulator system used in that series was checked out to assure electrical and mechanical correspondence to design specifications. Each time a problem was noted by either an operator or experimenter during any test, that test was terminated and the problem corrected.

The two manipulator systems studied here are the aforementioned RAM/TPC and ESAM/Analog Joystick. RAM was housed in the back half of the RAM/TPC room, as illustrated in Figure 4.1, and mounted upon a moveable carriage. RAM and its supporting equipment were screened from the operator's direct view by heavy black drapes. This supporting equipment in the back half of the test site included cameras, lighting, power amplifiers, air conditioning,



1 MANIPULATOR MOUNTS
2 ESAM
3 TASK MODULE
4 TV SYSTEM SENSORS
5 EXPERIMENTER'S STATION
6 SCENE LIGHTING

1 SUBJECT'S STATION
2 TV DISPLAY
3 MANIPULATOR CONTROL (ANALOG/JOYSTICK)

1 STORAGE

1 COMPUTER ROOM
2 PROGRAM-MER'S STATION

1 MANIPULATOR CARRIAGE
2 RAM
3 TASK MODULES
4 TV SYSTEM SENSORS
5 SUBJECT'S STATION
6 MANIPULATOR CONTROL (TPC)
7 EXPERIMENTER'S STATION

1 MINOR REPAIR
2 SMALL COMPONENT CHECKOUT

Figure 4-1. MANIPULATOR EVALUATION LABORATORY FUNCTIONAL LAYOUT and, at the task site, the task module, which contained the specific elements for the test at hand. The task was controlled from the operator's station with the RAM and ESAM operator stations varying slightly from one another. The RAM operator was seated in the forward half of the RAM/TPC room in front of the control display console with the TPC positioned to the right of the operator. He viewed the task from two camera angles and an enlarged view of either one of the two. For RAM, the experimenter was stationed in the test area, behind the black drape and recorded test events using electrical feedback and direct vision. The computer, which was intermediate in the RAM/TPC system, was housed in a separate room next to the RAM, so that operational noises and light could be controlled at the operator's site.

ESAM was set up in its test room along with it's support equipment including lights and cameras, and as in the RAM situation, the experimenter was stationed at the test site so direct visual observations concerning operation of the manipulator could be made. The task module was positioned in the room and the same conditions of environmental control established. The operator's station varied somewhat, in that the Analog/Joystick controller had to be placed between the operator and the TV monitors. This meant the operator sat slightly farther away from the TV monitors in ESAM tests than he did in RAM tests. Also, in operating the ESAM only the two angular views of the task were available from the 7 in. monitors, there was not an enlarged view of either available to the operator as there was in RAM tests. The operator was set up in his own room, and enclosed in a fabric tent for control. Communications between the experimenter and operator was mantained via headsets, whereas direct verbal communication was available in the RAM situation.

With the exception of specific hardware imposed constraints, every effort was made to ensure that both ESAM and RAM tests were conducted under identical conditions.

4.2 Minimum Position Test Apparatus and Procedure

Test Subjects

Five male subjects were selected for the minimum position change test. These subjects completed the testing program using the RAM/TPC configuration and then completed the ESAM/Analog configuration. Qualification criteria were right-hand dominance, normal vision acquity, ages 21 to 45, and an engineering backgoound. Each subject was trained for a minimum of 1 hour on each system; or until he could comfortably perform a 4 quadrant touch task with the manipulator.

Apparatus

The minimum position change test was designed to evaluate the time required for a manipulator system to complete a fine movement of the tip requiring fixed amplitude and tolerance of movement. The task module employed was a 30.5 by 30.5 cm (1 by 1 foot) square of black phenolic. The module contained 17 aluminum discs arranged in a cruciform pattern. The contacts included a center position and sixteen target contacts representing all possible combinations of four levels of movement amplitude and four levels of tolerance (contact diameter). The task module was sand blasted to prevent glare. It was mounted normal to the X axis of the manipulator system and at about 75% of the manipulator reach in the X axis. The task board could be rotated to require a certain movement in any direction in the YZ plane. The dimensions of the task module are shown in Figure 4-2.

A stylus was constructed using 2.54 by 2.54 cm (1 by 1 in.) phenolic. Embedded in this was an aluminum probe extending about 2.54 cm (1 in) beyond the phenolic. The probe was 5 mm. (.25 in) in diameter with a leveled

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

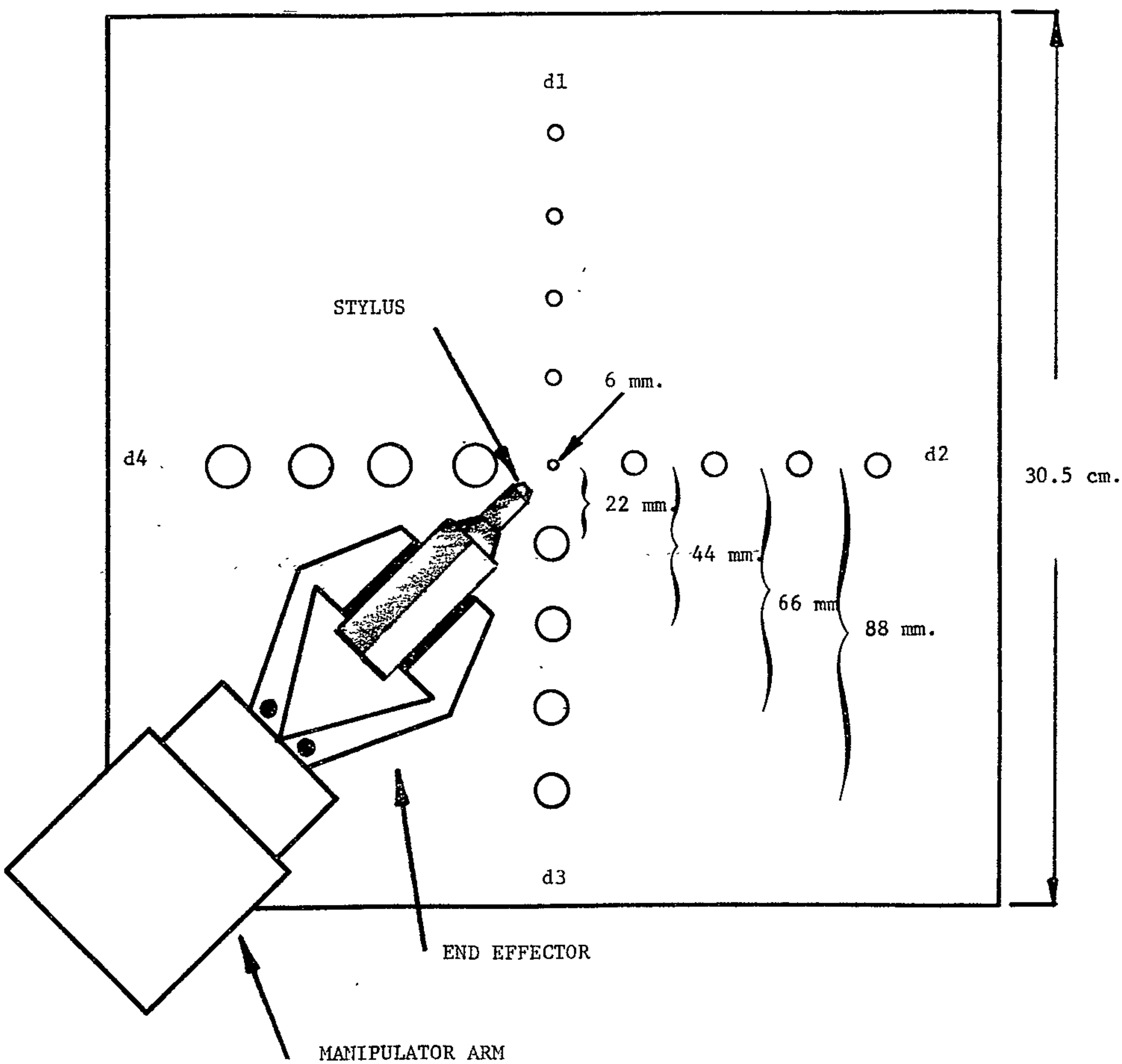


FIGURE 4.2: TASK MODULE FOR MINIMUM POSITION CHANGE TEST
(NOT DRAWN TO SCALE)

tip. The contact area was π^2 mm in area. A 12 volt dc power source was employed to close a circuit through the stylus and contact. The circuit included a set of relays and switches to start an electronic timer when contact was broken at the center disc. The timer was stopped when the correct target disc was contacted. This yielded a measure of movement time.

Experimental Design

The independent variables included the following:

4 target object sizes

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

4 conditions of target separation from the central target (center to center)

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

8 task board orientations

1) 0° -North
2) 45°
3) 90° -East
4) 135°
5) 180°
6) 225°
7) 270°
8) 315°

The control variables were set at the following levels:

TV image geometry

1) Fixed camera - normal to task, looking down over arm
2) Mobile camera - Approximately 90 degrees to right of fixed camera.

TV parameters

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

Lighting level - at task board

1) 100 foot candles

Initial distance from stylus tip to task board center

1) 25 cm (10 in.)

The dependent measures recorded were:

1) Elapsed time to move from initial position to center point contact.

2) Time to complete positional change from center to commanded target.

3) Accuracy of commanded positional change in terms of the number of incorrect targets contacted per trial.

Procedure with RAM System and ESAM System

Each subject received instructions from the experimenter and appropriate training trials using direct vision. After the training trials the experimenter recorded the base line information on test type tasks. Following training, the experimental trials began with the subject viewing the arrangement of targets on the task module through the TV monitor. The sequence began with the subject moving the end effector from a reference position and contacting the central target with the stylus. The signal denoting contact was sent to an experiment recorder, with the experimenter observing the test procedure at the test site. After 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 central target 0. That is, left-3 means moving away from 0 to the 3rd target on the left of the task module. When the subject made contact with the commanded target, an impulse was sent to the recorder and also terminated a digital clock in the experimenter's station. The digital clock was active from the time contact with target 0 was broken until contact was made with the commanded target. After contact, the experimenter verbally commanded the subject to return the stylus to "rest" and then proceeded to next trial. Sixteen trials were run for each of 8 orientations for a total of 128 trials. In each orientation there were 4 trials for each of the 4 target sizeband separations. Five subjects each completed the 128 trials, for a total of 640 trials.

The notion of utilizing a tasktime manipulator-to-hand ratio as a measurement of system merit (Vertut, 1973) necessitated running the series of minimum position change trials under a manual/direct vision procedure. This allows comparative measures to be developed between systems.

Procedure with Manual/Direct Vision

All testing was conducted with the subject standing at arm's length in front of the mounted task board and the center contact at eye level. Each trial began with the subject holding the metal-tipped stylus in his right hand and his arm drawn back to the reference or home position as when one prepares to throw a dart. Upon the verbal instruction of the experimenter, the subject closed and contacted the center target, then closed with, and contacted the designated target. Following contact with the designated target, the subject was instructed to return to the home position. This procedure was repeated for each of the targets within each of the task board orientations. Each subject manually completed the 16 trials for each of the eight board positions for a total of 128 trials per subject.

5.0 RESULTS

The raw data from the minimum position change test for both the RAM/TPC and ESAM/ANALOG joystick manipulator systems were subjected to a five-way analysis of variance. This analysis assumed a treatments-by-subjects experimental design with all factors fixed except subjects. The resulting source table is shown in Table 5-1.

Movement Time Data

The difference between manipulator systems was found to be highly significant ($\alpha < .01$). Averaging over all other independent variables, the mean times to complete the center to target motion for the RAM and ESAM systems were 37.25 and 11.39 seconds respectively. On the average, the ESAM system was thus able to complete the motions required in less than one-third the time required by the RAM system for the range of motions required during the test.

The main effect of target size was also found to be highly significant ($\alpha < .01$). The time required for a motion increases as the target size decreases. This result is in accord with Fitt's Law. The effect of target size, however, is dependent on which system is being employed as is indicated by the significant interaction between manipulator system and target size ($\alpha < .05$). The joint effects of target size and manipulator system are shown in Figure 5-1. The decrease in movement time with increasing target size for the ESAM/TPC system may be seen to be very nearly linear. The corresponding function for the RAM/TPC system shows departure from linearity. The time required for the smallest target size of 6.5 mm. (.25 in.) appears to be disproportionately large compared to a linear trend fitted to the function. This may suggest small amplitude instability during fine pointing control with the RAM/TPC

TABLE 5-1.

ANALYSIS OF VARIANCE OF MOVEMENT TIME

SOURCE	DF	SS	MS	F
MEAN	1	756802.5	756802.5	84.4911
SYSTEM	** 1	213960.6	213960.6	102.2083
TGT SIZE	** 3	25791.08	8597.040	14.9824
AMPLITUDE	* 3	7093.520	2364.510	4.7837
MOTION DIR	** 7	24072.08	3438.885	4.0330
S	4	35828.16	8957.040	
NQ	* 3	7768.520	2589.510	5.1830
ND	3	172.2662	57.42203	.1197
QD	9	2385.510	265.0637	.4745
NA	* 7	21067.08	3009.635	3.2486
QA	21	19253.08	916.8462	1.0944
DA	21	9865.540	469.7981	.8083
NS	4	8373.540	2093.385	
QS	12	6885.770	573.8150	
DS	12	5931.520	494.2981	
AS	28	23875.08	852.6900	
NQD	9	3727.635	414.1731	.6809
NQA	21	18286.08	870.7837	1.0752
NDA	21	10226.04	486.9544	.7757
QDA	* 63	41664.16	661.3150	1.3645
NQS	12	5995.520	499.6262	
NDS	12	5758.770	479.8919	
QDS	36	20109.08	558.5962	
NAS	28	25941.08	926.4400	
QAS	84	70372.32	837.7837	
DAS	84	48824.16	581.2212	
NQDA	** 63	46454.16	737.3775	1.4885
NQDS	36	21899.08	608.3150	
NQDS	84	68032.32	809.9087	
NQAS	84	52732.16	627.7525	
QDAG	252	122136.3	484.6731	
NQDAS	252	124836.3	495.3762	

** $p < .01$
* $p < .05$

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system. It may also be noted that linear trends fitted to the data of Figure 5-1 would show a greater slope for the RAM/TPC system than for the ESAM/ANALOG system. The impact of reduced target size on movement time is greater for the former than for the latter. The effect of target size is also consistent with Fitt's law

The main effect of movement amplitude was also found to be significant ($\alpha<.05$). Movement time increases with movement amplitude. The main effect of amplitude is illustrated in Figure 5-2. The function does not appear to be linear as it would if a constant velocity were maintained and travel distance increased. Rather, the function appears to be negatively accelerated. This result is consistent with Fitt's law which supposes that movement time is linearly related to the logarithm of amplitude.

The main effect of motion direction and interaction of motion direction with manipulator system were found to be significant at $\alpha<.01$ and $\alpha<.05$ respectively. These effects are illustrated in Figure 5-3 which shows mean movement time as a function of direction of motion with manipulator system as the curve parameter.

The data for the RAM/TPC system appear to reflect the limitations on pure Z-axis translation inherent in the control law. This law does not provide a pure Z-axis command. Such motion can only be obtained by combined motions of the other five degrees of freedom. This constraint is clearly reflected in the data. The direction of motion scale in Figure 5-3 refers to motion directions in a clock-face system. Thus zero refers to a pure upward motion, ninety refers to pure horizontal travel to the right etc. The minimum times for the RAM/TPC systems are obtained at 90 degrees and 270 degrees representing pure horizontal motion. Worst case times occur at 0 degrees and 180 degrees representing pure Z-axis motion. Intermediate

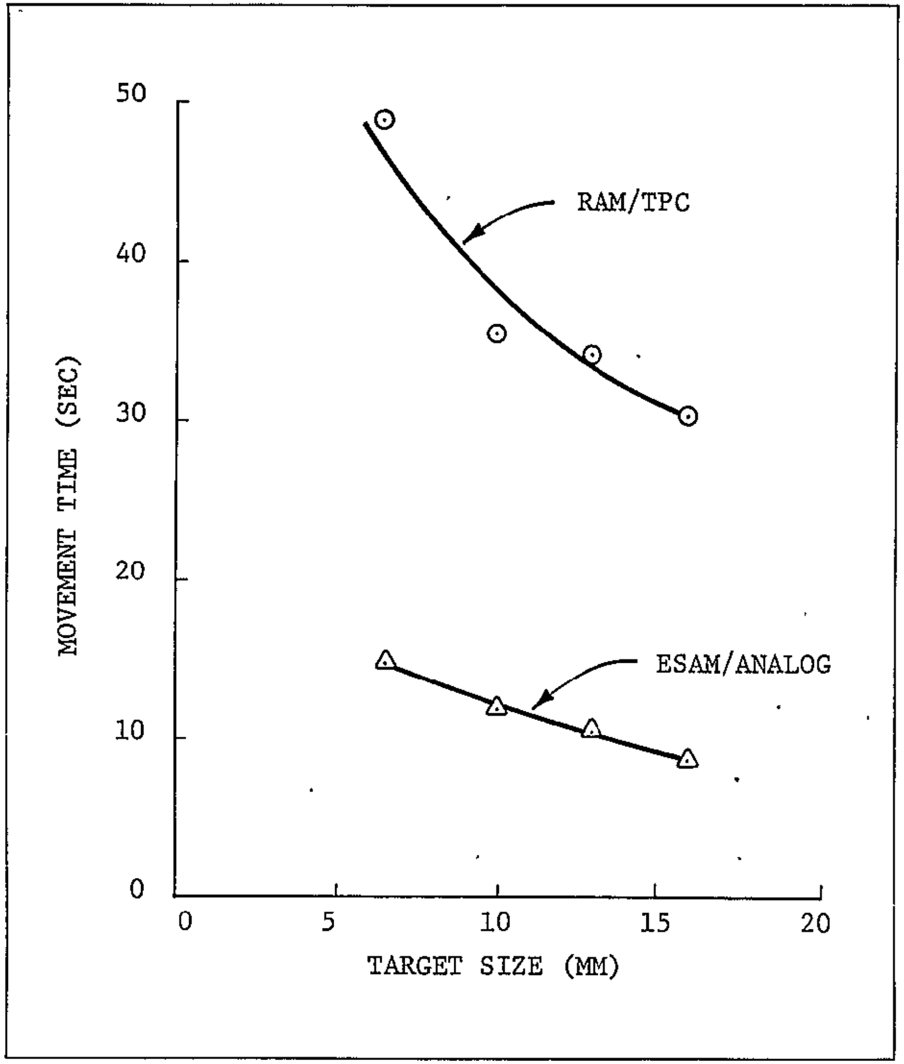

FIGURE 5-1. MOVEMENT TIME AS A FUNCTION OF MANIPULATOR SYSTEM AND TARGET SIZE

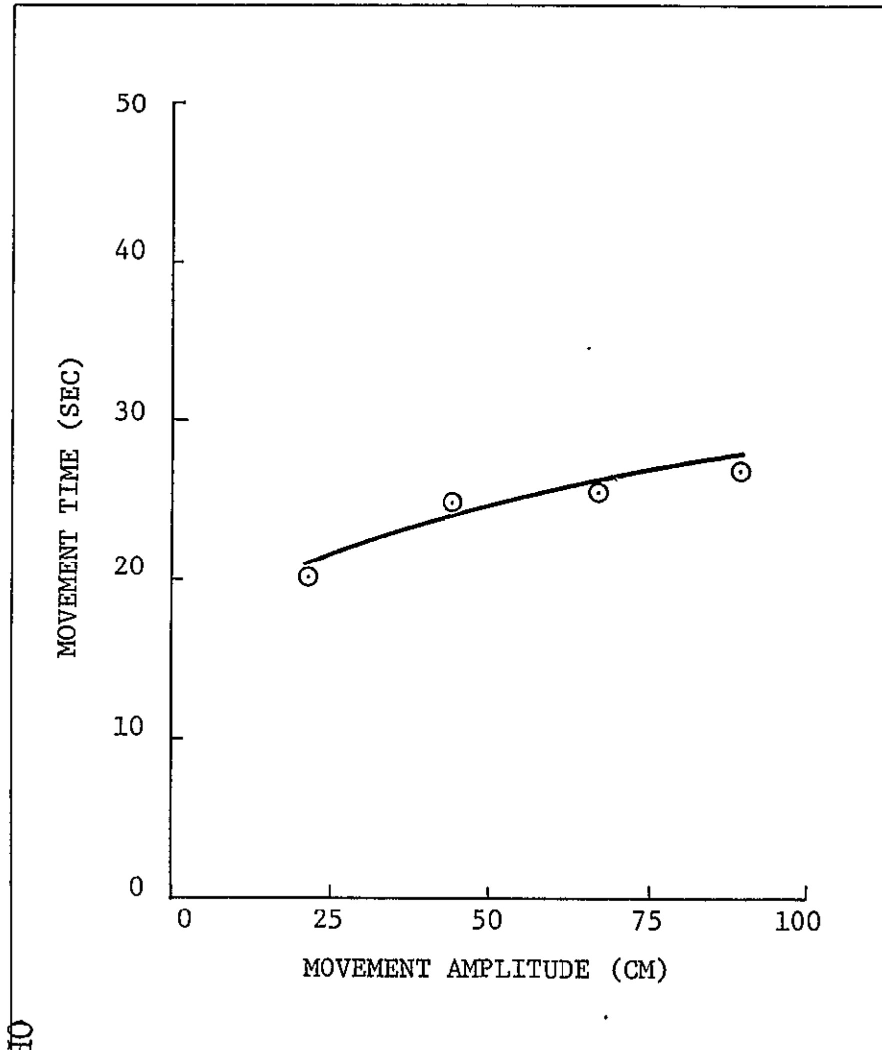

FIGURE 5-2. MOVEMENT TIME AS A FUNCTION OF MOVEMENT AMPLITUDE

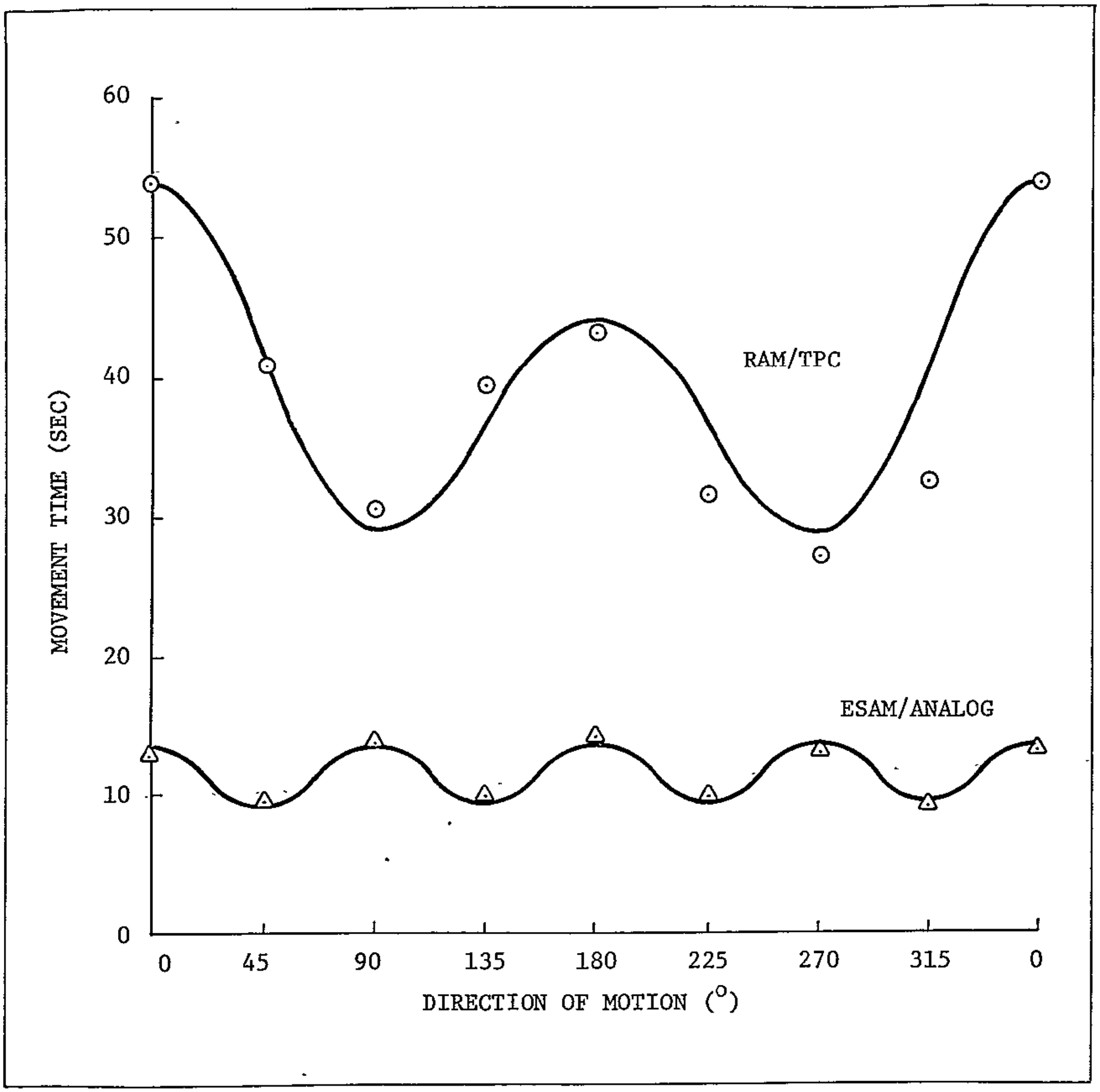

FIGURE 5-3. MOVEMENT TIME AS A FUNCTION OF MANIPULATOR SYSTEM AND MOVEMENT DIRECTION

directions which involve both motions yield intermediate results.

The data for the ESAM system show less variance due to motion direction than do the RAM data. The differences between means at the various levels of motion direction for the ESAM/ANALOG system were found to not reach the .10 significance level by Scheffe test. This suggests that the variation with motion direction for the RAM/TPC system shown in Figure 5-3 represents only sampling error. The difficulty with this interpretation, however, is that the variation shows a consistent pattern. The single axis motions whether up, down, left, or right appear to require more time to complete than do the diagonal motions which contain components along two axes. This result is difficult to account for if it is supposed that control of two degrees of freedom is required by diagonal motions but that control of one degree of freedom is necessary for single axis motions. It would then seem that diagonal motions should be more difficult than single axis ones and that the former would require more time for completion. If the movement direction variance is not simply sampling error, the results indicate that holding one axis at zero is more difficult than commanding a motion in that axis.

The RAM/TPC data in Figure 5-3 support this notion since movement time takes on intermediate values for diagonal motions. If difficulty depended on the number of axes involved, diagonal motions should yield the greatest completion times. Instead, the RAM data suggest that difficulty depends on the degree of involvement of Z-axis motion.

This interpretation is questionable, however, due to the lack of significant simple effects of motion direction for the ESAM/ANALOG data. Furthermore, the shape of the RAM/TPC curve may reflect the nature of the controller, the difficulty of producing Z-axis movements aiding performance at 90 degrees and 270 degrees where such motion is inappropriate. Difficulty in holding the X-axis at the null position with the TPC may, however, contribute to the worst case times at 0 degrees and 180 degrees. This would agree with the statement of the operators that inadvertant cross-coupling of axes was a problem with the RAM/TPC system.

Relation of Movement Time to Index of Difficulty

The remaining significant sources of variation in Table 5-1 are higher order interactions involving all four independent variables. The nature of Fitt's law would lead one to expect interactions of this sort given that manipulator movement time is a function of index of difficulty. This is so because Fitt's law supposes that movement time depends on the ratio of amplitude and tolerance. Interactions should occur for any theoretical function in which movement time is not due to independent additive combinations of amplitude and movement time. Within the present effort, performance of separate manipulator systems is of primary interest. Effects obtained by averaging across manipulator systems are not particularly meaningful. Therefore, the four-way interaction but not the three-way interaction is of interest.

The four-way interaction indicates that the joint effects of movement amplitude and tolerance vary depending on manipulator system and direction of motion. To illustrate these effects, the task module dimensions (amplitude and tolerance) were substituted in eq. 2-1 to obtain the index of difficulty values for each combination of amplitude and tolerance. These values are shown in Table 5-2.

The linear correlation coefficient between index of difficulty and movement time was obtained for each combination of manipulator system and direction of motion. The statistics resulting from this analysis are shown in Table 5-3. Table 5-3 lists the mean movement time which corresponds to manipulator system by motion direction means plotted in Figure 5-3. The intercept and slope parameters shown in Table 5-3 give the constants for straight lines fitted to the data by the method of least squares. The best

Table 5-2 Index of Difficulty Values for the Minimum Position Change Task Module

Target Diameter (mm)	Movement Amplitude (mm)	Index of Difficulty (bits)
6.5	22.5	2.79
6.5	44.0	3.76
6.5	67.0	4.36
6.5	90.0	4.79
10.0	22.5	2.17
10.0	44.0	3.14
10.0	67.0	3.74
10.0	90.0	4.17
13.0	22.5	1.79
13.0	44.0	2.76
13.0	67.0	3.36
13.0	90.0	3.79
16.0	22.5	1.50
16.0	44.0	2.46
16.0	67.0	3.07
16.0	90.0	3.49

TABLE 5-3. CORRELATION ANALYSIS STATISTICS

RAM/TPC

Direction	Mean	Int.	Slope	r	F
0	53.77	7.35	14.52	.325	9.201**
45	40.78	13.07	8.67	.276	6.406*
90	30.50	7.33	7.25	.249	5.149*
135	39.38	36.87	.79	.020	.032
180	42.96	12.52	9.52	.292	7.283**
225	31.35	10.50	6.52	.237	4.624*
270	26.98	27.13	- .05	- .001	.000
315	32.24	18.36	4.34	.148	1.747

ESAM/ANALOG

Direction	Mean	Int.	Slope	r	F
0	12.71	1.90	3.38	.372	12.504**
45	9.34	1.14	2.57	.451	19.962**
90	13.68	9.33	1.36	.099	.770
135	9.85	1.72	2.54	.457	20.549**
180	14.03	2.34	3.66	.336	9.941*
225	9.80	1.87	2.48	.442	18.952**
270	12.71	- 2.68	4.82	.398	14.705**
315	8.97	- 3.73	3.98	.571	37.778**

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

fitting function relating index of difficulty to movement time in the linear fashion demanded by Fitt's Law is thus a straight line having the indicated intercept and slope. The correlation coefficients give the degree to which deviations from the mean movement time are systematically related to the index of difficulty. The final column of Table 5-3 shows the F-ratio associated with the correlation coefficient. This F-ratio shows the ratio of regression variance to error variance. It is tested using one and seventy-eight degrees of freedom. The asterisks in Table 5-3 give the significant levels.

Inspection of Table 5-3 suggests that for both manipulators, Fitt's law does apply to the data. The effect of index of difficulty on movement time is more pronounced for the ESAM/ANALOG system than for the RAM/TPC system. In the ESAM/TPC data, seven out of eight motion directions yield significant correlations between movement time and index of difficulty. The 90 degree (rightward) motion alone fails to show a significant correlation. The 180 degrees motion (straight down) correlation is significant at the .05 level. The remaining correlations reached the .01 level of significance.

In the case of the RAM/TPC data, the 135, 270, and 315 degree motions failed to produce significant correlations between movement time and index of difficulty. The 45, 90, and 225 degree movements yielded correlation coefficients significant at the .05 level. Only the correlations obtained from the 0 and 180 degree motions (straight up and straight down respectively) reached the .01 level. In terms of the number of significant correlation coefficients and their general magnitude, the ESAM/ANALOG data show a greater degree of correlation between movement time and index of difficulty. The magnitudes of the correlations reflect the fact that they are computed from single movement times. Response times in most tasks are highly variable and contain considerable random variation.

To illustrate the results obtained via the correlation analysis, the scatter plots of mean movement time against index of difficulty and the least squares regression lines are presented in Figures 5-4 through 5-11. Each figure shows the data for the two manipulator systems at one direction of motion. The data points plotted are the mean times, each of which is based on five observations. The regression lines are those fitted to the single trial data and thus reflect all the data. Deviations from the regression line in Figures 5-4 through 5-11 thus represent departures of specific amplitude/tolerance combinations from the general trend of the data.

Figure 5-4 shows the zero degree data. As indicated in Table 5-3, the correlations for both systems are significant at the .01 level. The RAM/TPC times increase about four times as rapidly with respect to index of difficulty as do those for the ESAM/ANALOG system. The difference in slopes shows that movement time ratios for the two manipulator systems would depend strongly on the index of difficulty. Figure 5-5 shows the movement time data for 45 degrees. Both correlations are significant at 45 degrees, however, the magnitude of the RAM/TPC correlation is .276 where that for the ESAM/ANALOG data is .451. The difference is illustrated in the greater degree of spread for the RAM/TPC data as opposed to the ESAM/ANALOG data. The two regression lines are separated by an intercept difference of about twelve seconds and the RAM/TPC slope is about three times as great as that for the ESAM/ANALOG data. The movement time ratio at this movement angle thus depends on index of difficulty.

The 90 degree movement data are shown in Figure 5-6. In this case, the movement time/index of difficulty correlation was found to be significant at the .05 level for the RAM/TPC system but not for the ESAM/ANALOG system.

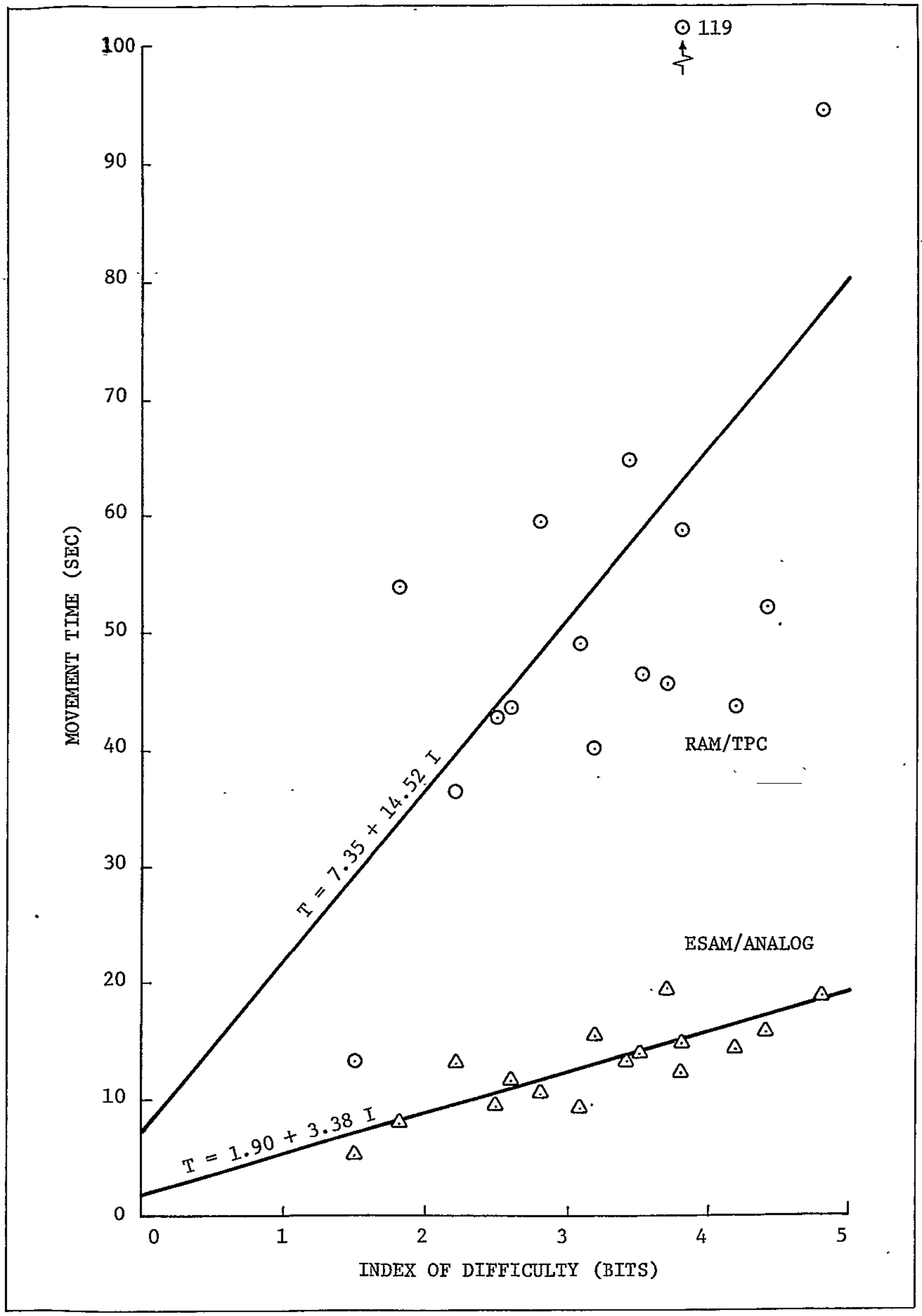

FIGURE 5-4. MOVEMENT TIME AS A FUNCTION OF INDEX OF DIFFICULTY FOR 0 DEGREES

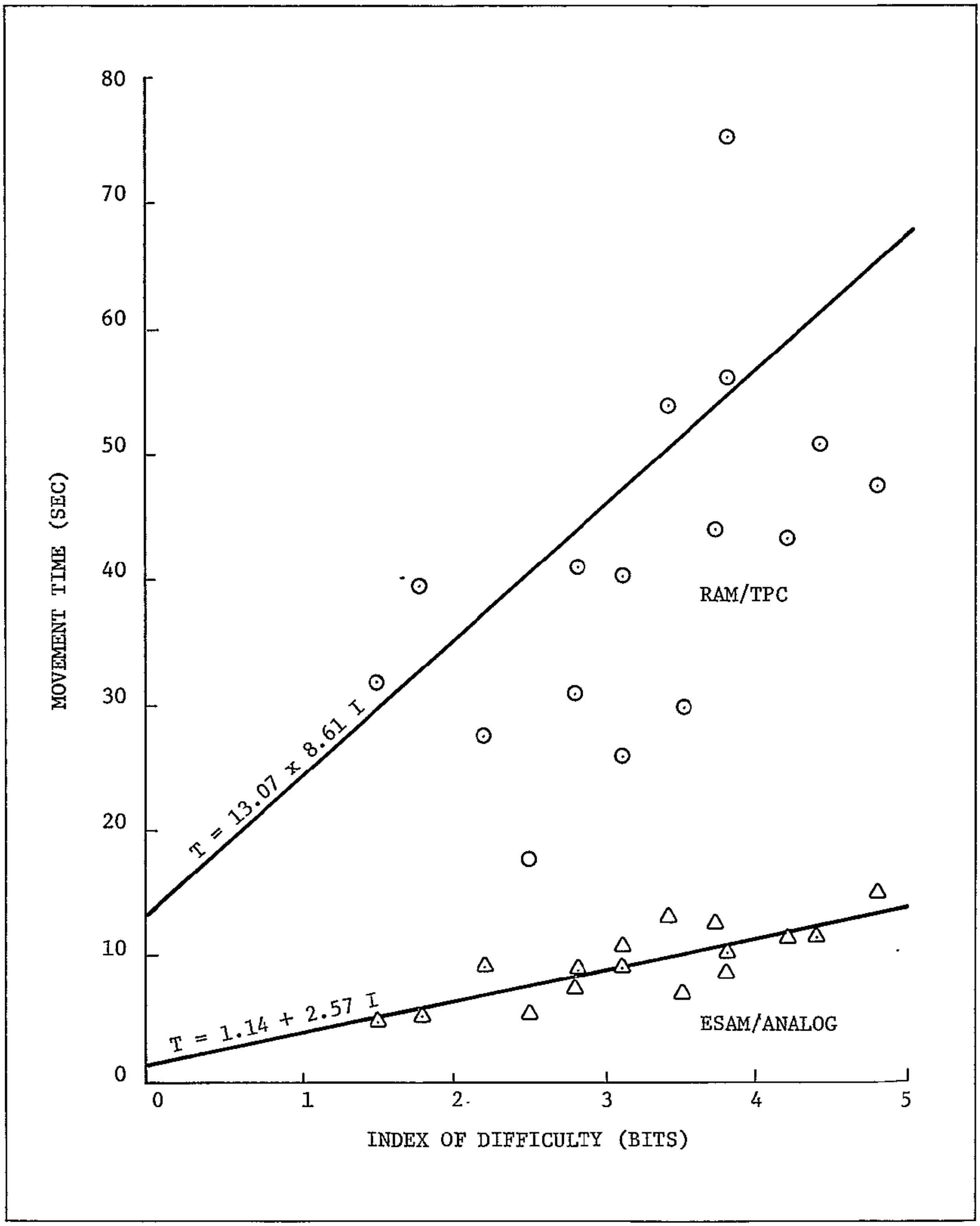

FIGURE 5-5. MOVEMENT TIME AS A FUNCTION OF INDEX OF DIFFICULTY FOR 45 DEGREES

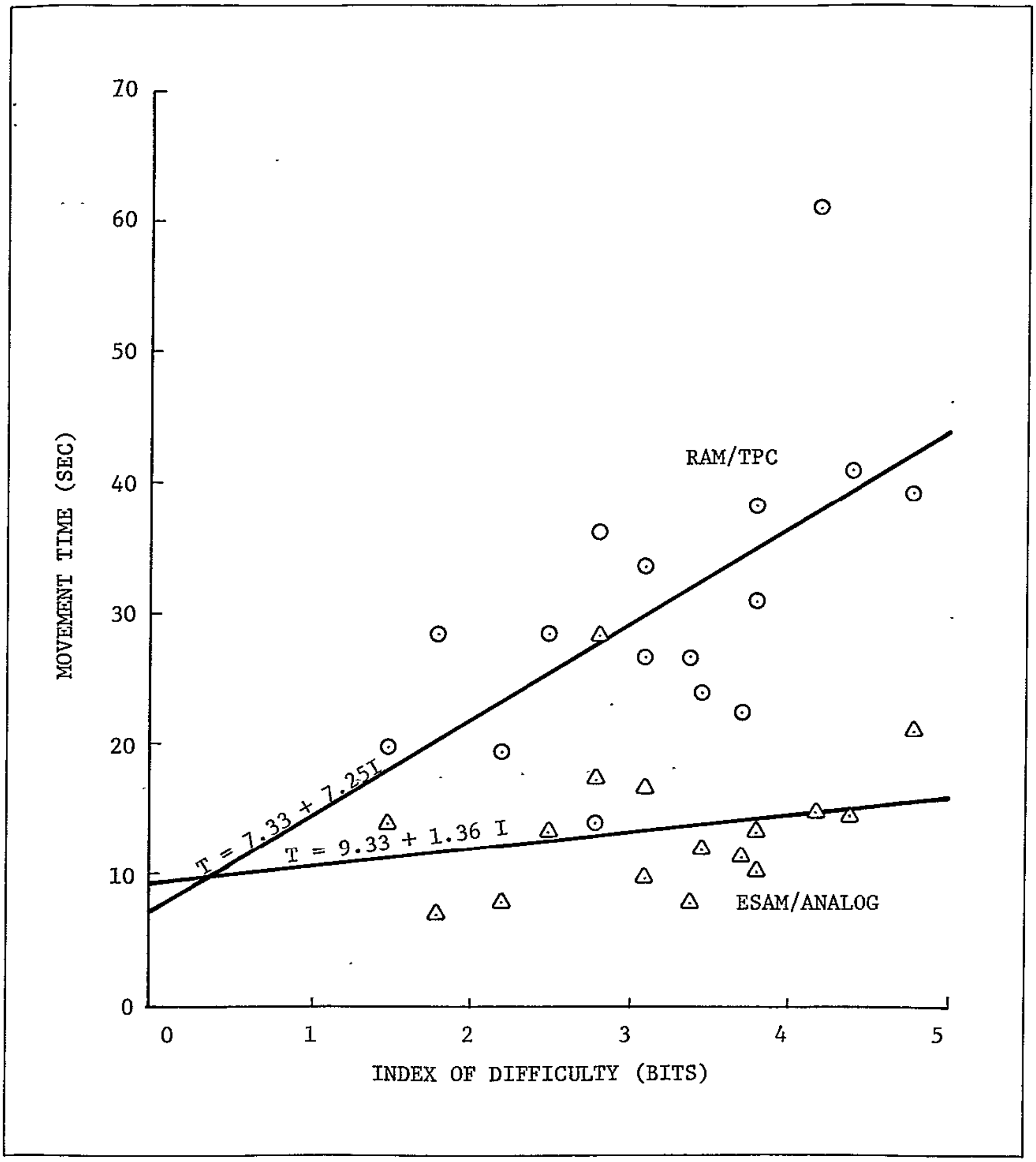

FIGURE 5-6. MOVEMENT TIME AS A FUNCTION OF INDEX OF DIFFICULTY FOR 90 DEGREES

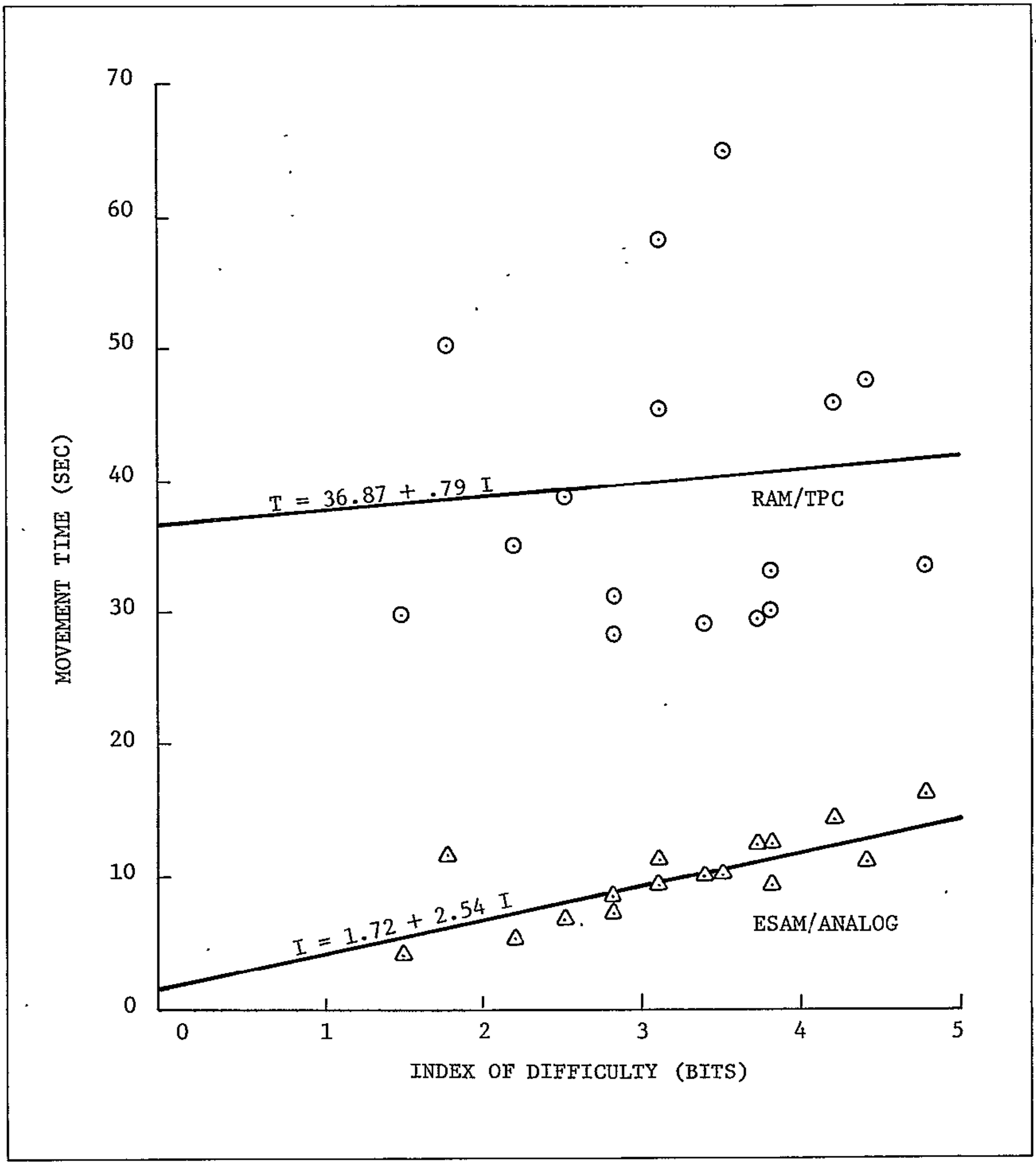

FIGURE 5-7. MOVEMENT TIME AS A FUNCTION OF INDEX OF DIFFICULTY FOR 135 DEGREES

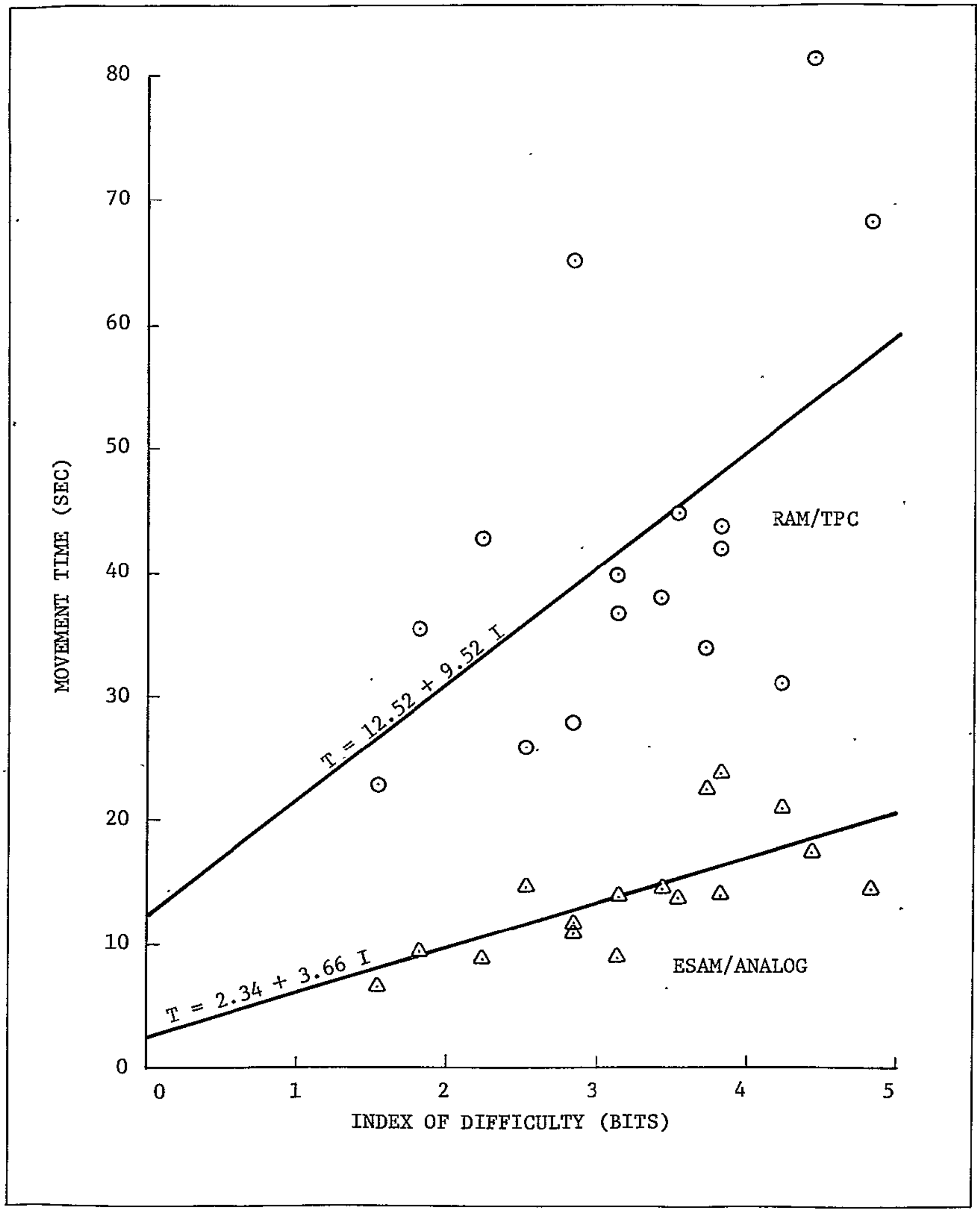

FIGURE 5-8. MOVEMENT TIME AS A FUNCTION OF INDEX OF DIFFICULTY FOR 180 DEGREES

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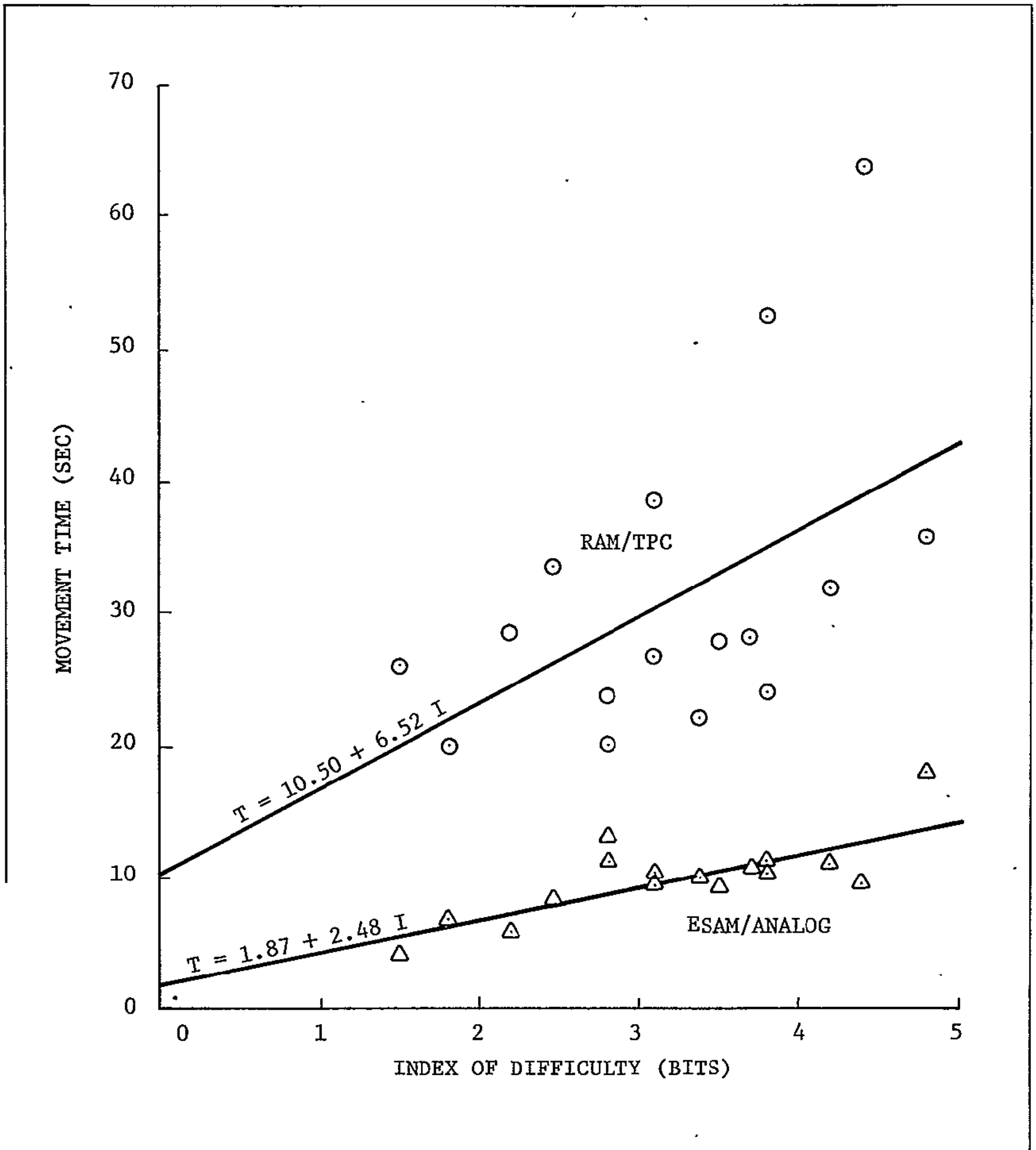

FIGURE 5-9. MOVEMENT TIME AS A FUNCTION OF INDEX OF DIFFICULTY FOR 225 DEGREES.

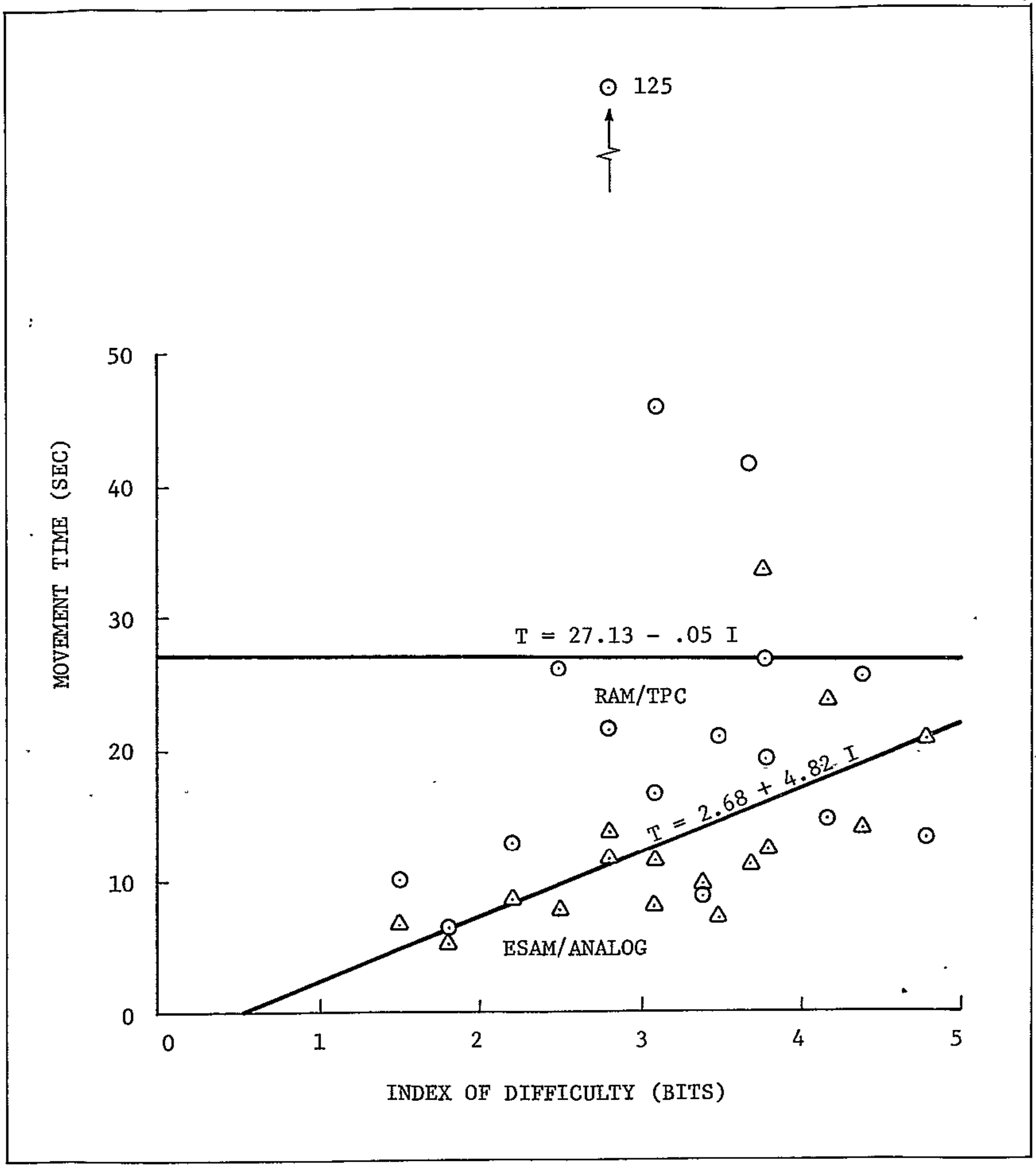

FIGURE 5-10. MOVEMENT TIME AS A FUNCTION OF INDEX OF DIFFICULTY FOR 270 DEGREES

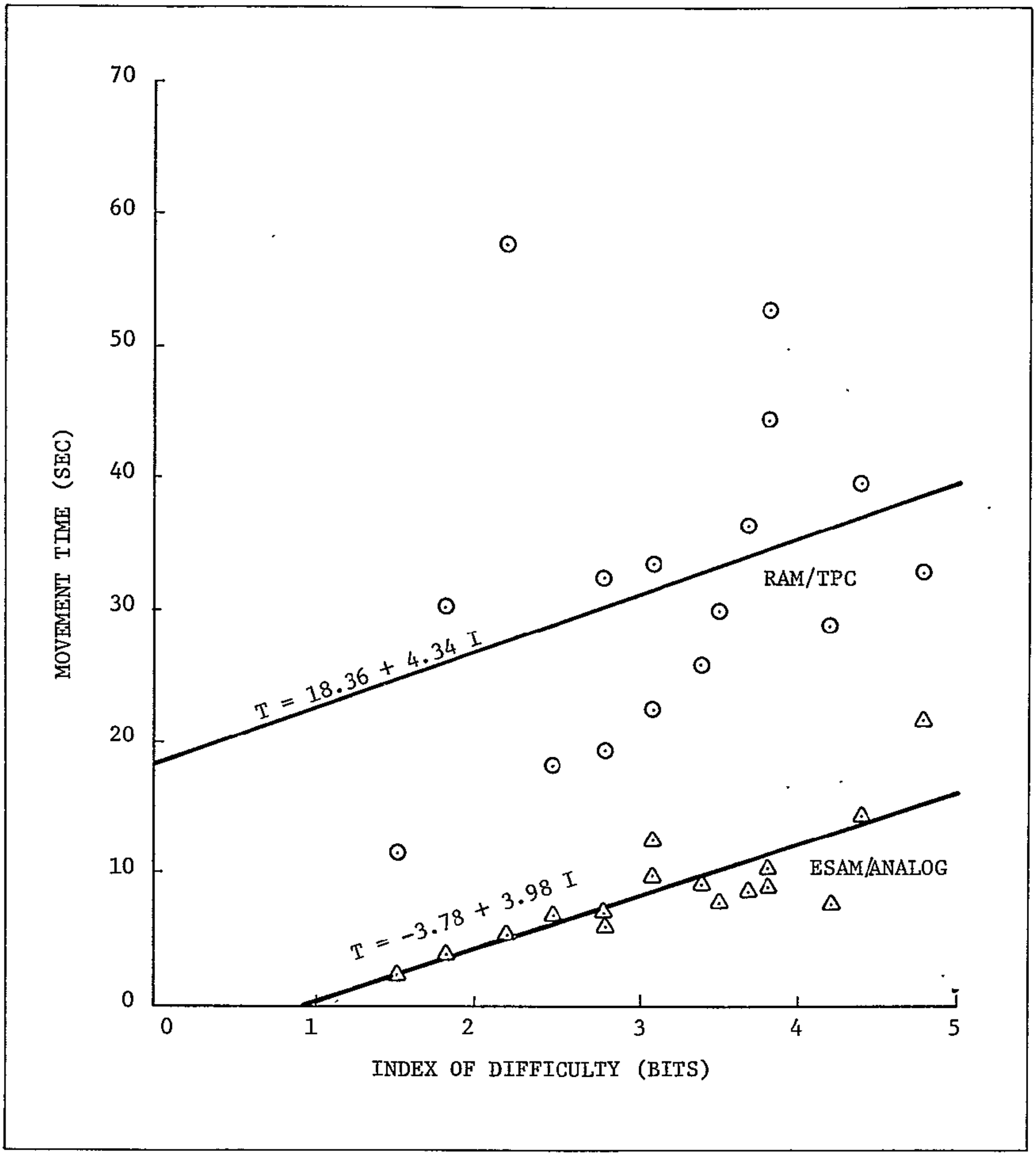

FIGURE 5-11. MOVEMENT TIME AS A FUNCTION OF INDEX OF DIFFICULTY FOR 315 DEGREES

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The movement time for the latter may be regarded as having a constant mean of 13.68 seconds which is independent of index of difficulty. The RAM/TPC data show a significant increase in movement time with index of difficulty. Figure 5-6 shows a minimum separation between the movement times produced by the two systems compared to other movement directions.

Figure 5-1 shows the data for movements at 135 degrees. In this case, the correlation between movement time and index of difficulty was not found to be significant for the RAM/TPC data but reached the .01 level for the ESAM/ANALOG data. In this case, the movement time variation for the RAM/TPC system may be taken to represent random variation around a mean of 39.38 seconds. The ESAM/ANALOG data, however, appear to increase with index of difficulty at about 2.54 seconds per bit.

The data for the 180 degree movement are shown in Figure 5-8. Both correlations reached significant levels under this direction of motion. The systems are separated in Figure 5-8 by an intercept difference of about 10 seconds and the slope of the RAM/TPC regression line is 2.6 times that of the ESAM/ANALOG system. The time ratio for the two systems thus depends on index of difficulty for 180 degrees movements.

The 225 degree movement data are shown in Figure 5-9. In this case, both correlations between movement time and index of difficulty were found to reach significance. The RAM/TPC correlation coefficient was found to be .237 while that for the ESAM/ANALOG system was .442. The 225 degree data show a strong similarity to those for 180 degrees. The intercept difference for the former being about 9 seconds and the ratio between slopes being about 2.6.

Figure 5-10 shows the data for the 270 degree movement. The RAM/TPC movement times in this case were found to be independent of index of difficulty as indicated by the essentially zero correlation in Table 5-3. The correlation between movement time and index of difficulty for the ESAM/ANALOG system, however, reached the .01 significance level. The RAM/TPC data of Figure 5-10 may be taken as random variation around a mean of 26.98 seconds. The ESAM/ANALOG data, however, show an increase in movement time of 4.82 seconds per additional bit. It may also be noted that the intercept as estimated for the ESAM/ANALOG data is negative. This probably indicates that for extremely low information movements, the straight line relationship would become curvilinear. Within the range of index of difficulty studied here, however, there is little evidence of systematic departure from linearity within the data points. The separation between the movement times for the two systems appears to be at a minimum for the 270 degree movement. This result was also noted for movements in the 90 degree direction. Pure horizontal motion appears to represent a best case for the RAM/TPC system but a worst case for the ESAM/ANALOG system.

The data for the 315 degree condition are shown in Figure 5-11. The correlation between movement time and index of difficulty was not found to reach significance for the RAM/TPC data. That for the ESAM/ANALOG system, however, was found to be significant at the .01 level. The RAM/TPC data may thus be considered to represent random variation around a mean of 32.24 seconds. The ESAM/ANALOG data show a negative intercept and a slope of 3.98 seconds per bit.

To permit a graphic comparison of the available summary statistics, plots were constructed in a polar format. Figure 5-12 shows mean movement time as a function of motion direction and manipulator system. The axes of Figure 5-12 indicate direction of motion where the +Y axis represents

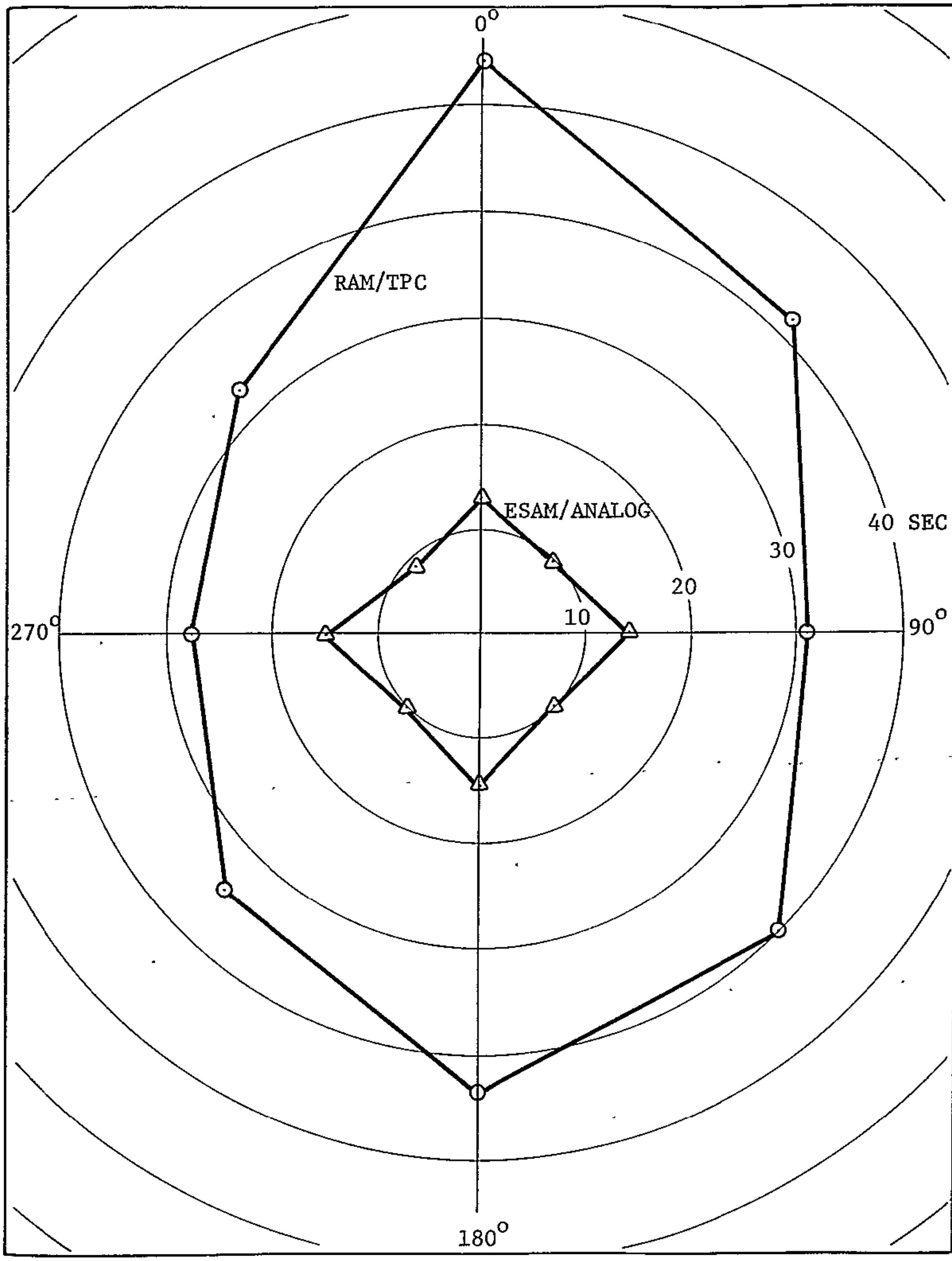

FIGURE 5-12. MEAN MOVEMENT TIME AS A FUNCTION OF MOTION DIRECTION AND MANIPULATOR SYSTEM

the zero degree motion. The +X axis represents 90 degree motion, etc. Radial distance indicates movement time in seconds. Thus, the innermost circle represents 10 seconds, etc.

Figure 5-12 provides a graphic indication of the mean movement time data. The discussion of Figure 5-3 applies to Figure 5-12 since the two figures are alternative plots of the same data. Figure 5-12 shows the increase in RAM/TPC movement time for vertical movements relative to horizontal ones previously discussed. In addition, there is a tendency for rightward movements to require more time than do leftward ones. In the case of the ESAM/ANALOG data, the reduction in movement time for diagonal movements relative to single axis movements may be seen. The data plot for the ESAM/ANALOG system, however, appears symmetrical in terms of movement time.

The correlation between movement time and index of difficulty for the combinations of system and movement direction is plotted in Figure 5-13. The generally greater correlations found for the ESAM/ANALOG data as compared with the RAM/TPC system are indicated by the larger envelopes of the former system. The ESAM/ANALOG system, however, shows a marked reduction in correlation at 90 degrees. The correlation envelope for the RAM/TPC system is collapsed at 135 and 270 degrees.

The fact that for certain motion directions, the correlation drops markedly suggests that the systems demonstrate random error in these directions. It could be argued that many functional forms could be fitted to the relationship between movement time and index of difficulty and one or more of these might show a higher correlation than would the form proposed by Fitt's. Regardless of the interpretation of the index of difficulty as an information measure, it seems reasonable to suppose that movement time should be monotonically related to the distance involved in the movement and to the inverse of target

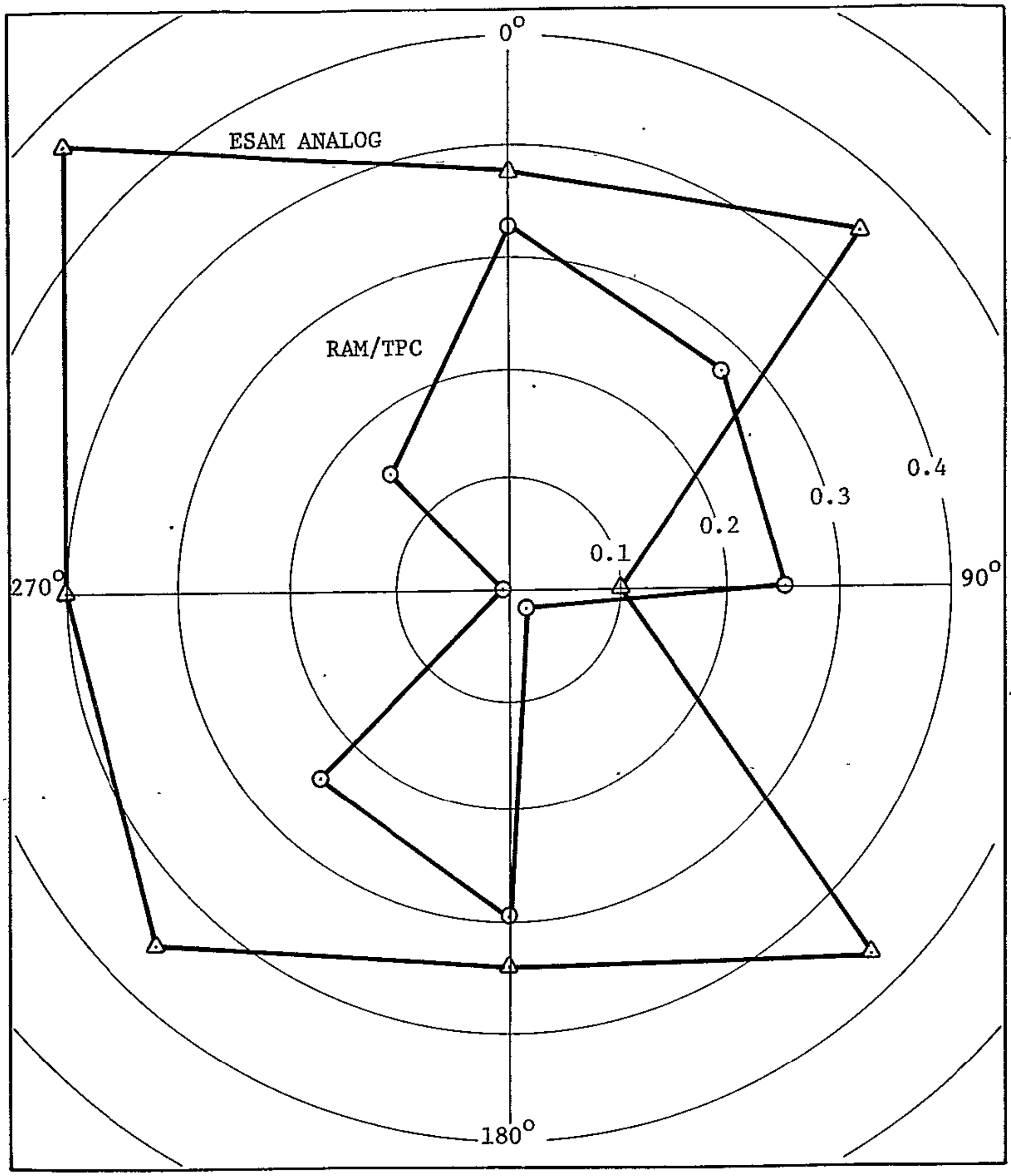

FIGURE 5-13. CORRELATION WITH ID MEAN MOVEMENT TIME AND INDEX OF DIFFICULTY AS A FUNCTION OF MANIPULATOR SYSTEM AND MOVEMENT DIRECTION

size. The data presented in Figures 5-4 through 5-11 suggest either fair correspondence with the functional form of Fitt's law or random variability independent of movement amplitude and target diameter. Where random variation is obtained, it seems reasonable to suppose that uncontrolled variation is present in the system.

To further examine this relationship, the variability of movement times as measured by the standard deviation was plotted in Figure 5-14. The ESAM/ANALOG data show the facilitation of performance for the diagonal movement cases compared with the single axis cases. The reduction in variability for diagonal motions, however, is more pronounced than the same effect for the mean times. Thus, the diagonal movements yield not only shorter average times but also less variability of time as compared to the single axis motions. The horizontal motions also yield greater variance than do vertical motions.

The RAM/TPC data of Figure 5-14 show consistently greater variation than do the ESAM/ANALOG data. The most notable feature of Figure 5-14, however, is the drastic increase in variability for 270 degree movements of the RAM/TPC system. Inspection of Figure 5-13, furthermore, shows the correlation of movement time with index of difficulty to be essentially zero for RAM/TPC 270 degree movements. The large increase in variance is therefore not a function of a reduced rate of information processing. It appears to represent almost entirely random variability. To make this result more explicit, the proportion of movement time accounted for by variation in index of difficulty is shown in Figure 5-15. The proportion drops to near zero at 270 degrees and 135 degrees for the RAM/TPC system and at 90 degrees for the ESAM/ANALOG system. Modifications to these systems should take into

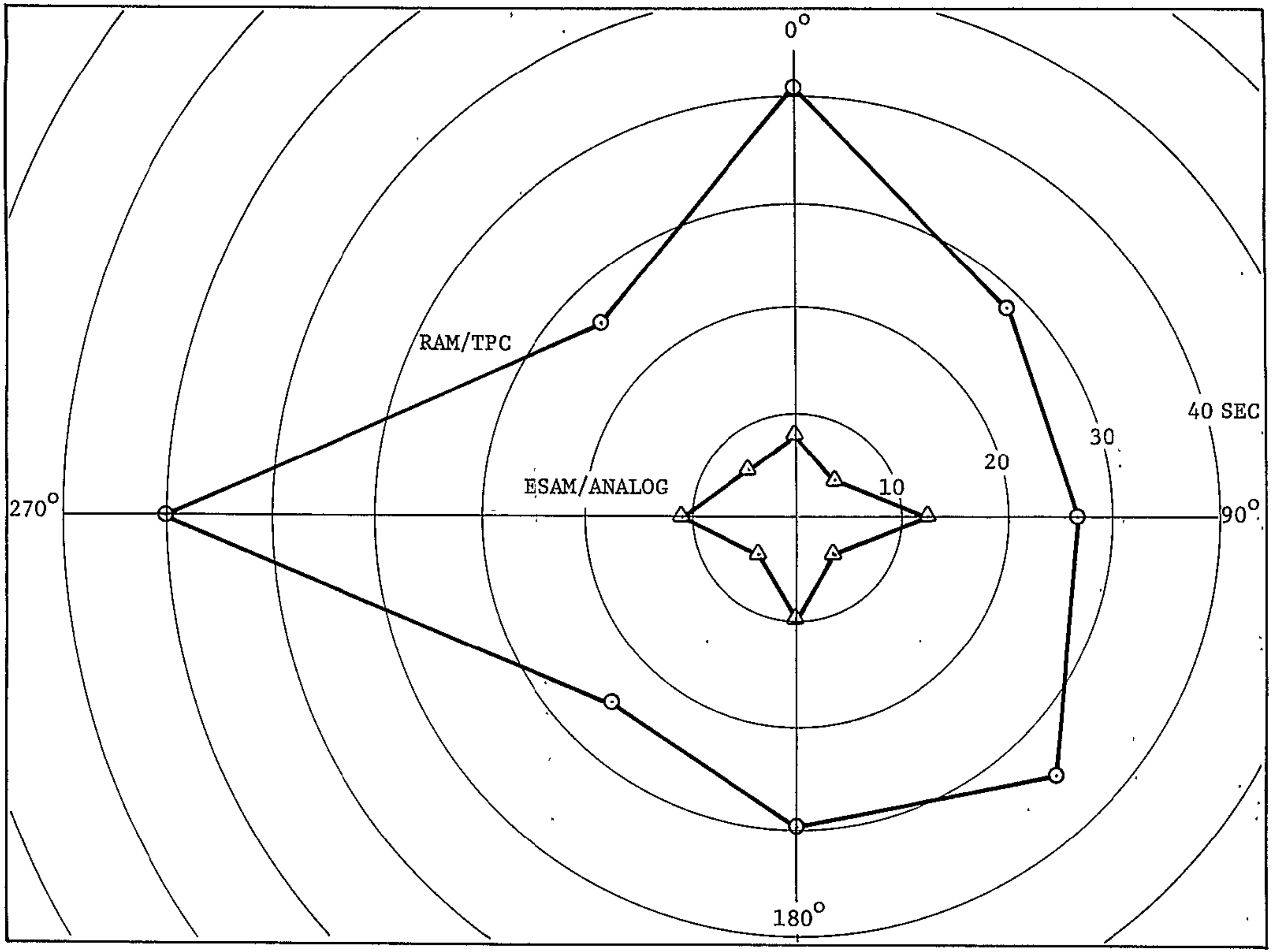

FIGURE 5-14. STANDARD DEVIATION - SEC.

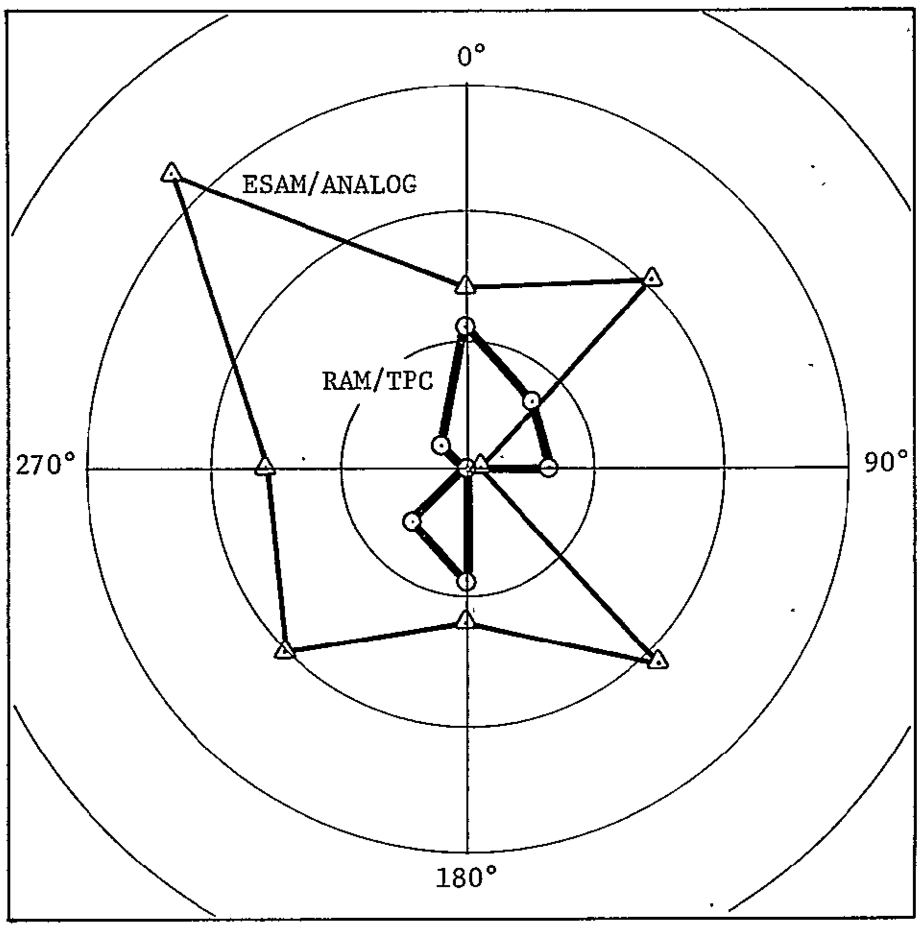

FIGURE 5-15. PROPORTION OF VARIANCE

account the random fluctuations in movement time at the motion directions mentioned.

Time Ratio Measures

The approach taken by Vertut (1973) expressed manipulator performance as a ratio of mean system movement time to the mean time required to accomplish the task by hand. To permit this type of analysis, the same subjects who participated in the manipulator tests also carried out the minimum position change task by hand. Each subject held the stylus directly in his dominant hand and the test procedure was carried out as during the manipulator tests.

The grand mean movement time for the manual test sequence was .423 second. The relationship between index of difficulty and hand movement time is shown in Figure 5-16. The data points of Figure 5-16 are each based on forty observations representing all combinations of five subjects and eight directions of motion. The linear function fitted to these data was found to have a slope of .103 seconds per bit. This value is somewhat greater than the value of .074 seconds per bit found by Fitts. The general trend of the data, however, co-responds closely to Fitt's law.

Because of the difference between intercept values, mean time ratios as proposed by Vertut would vary with index of difficulty. To avoid this variation and to yield a general time ratio figure of merit, the mean movement times for the manipulator systems under each direction of motion were divided by the grand mean of the hand time data. These ratios are shown in Table 5-4. The ratios obtained range from 63.78 to 127.12 for the RAM/TPC system and from 21.21 to 33.17 for the ESAM/ANALOG system. The corresponding values obtained by Vertut ranged from 1.5 to approximately 100. It should be noted, however, that Vertut's results were obtained using direct vision. The present data

TABLE 5-4.

DERIVED TIME MEASURES

RAM/TPC

Direction	Mean Time (Sec)	Manipulator to Hand Time Ratio	Information Processing Rate (Bits/Sec)	Hand Rate to Manipulator Rate Ratio
0	53.77	127.12	.069	140.72
45	40.78	96.41	.115	84.43
90	30.50	72.11	.138	70.36
135	39.38	93.10	---	---
180	42.96	101.56	.105	92.48
225	31.35	74.11	.153	63.46
270	26.98	63.78	---	---
315	32.24	76.22	---	---

ESAM/ANALOG

Direction	Mean Time (Sec)	Manipulator to Hand Time Ratio	Information Processing Rate (Bits/Sec)	Hand Rate to Manipulator Rate Ratio
0	12.71	30.05	.296	32.80
45	9.34	22.08	.389	24.96
90	13.68	32.34	---	---
135	9.85	23.29	.394	24.64
180	14.03	33.17	.273	35.57
225	9.80	23.17	.403	24.09
270	12.71	30.05	.207	46.91
315	8.97	21.21	.251	38.69

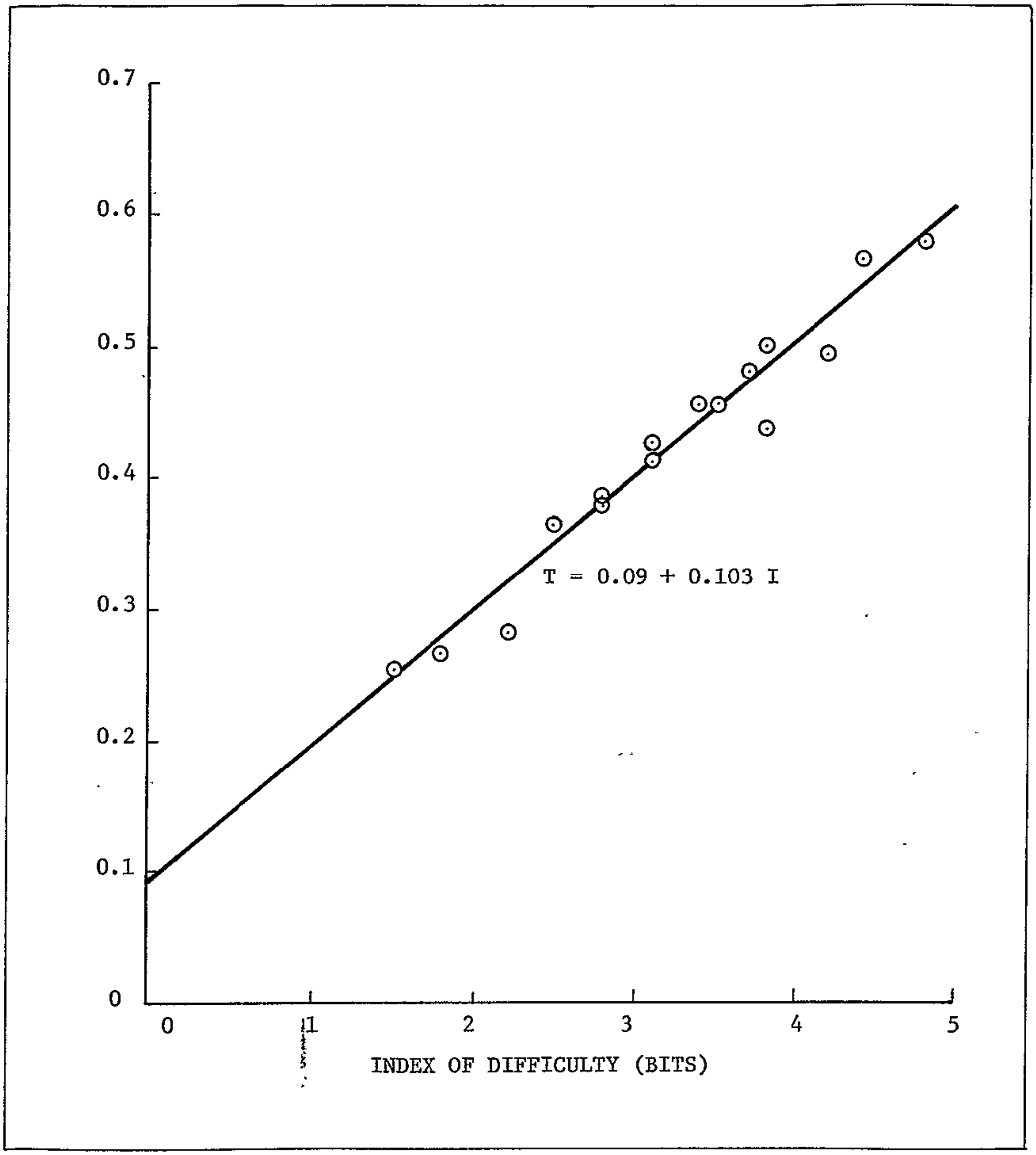

FIGURE 5-16. MOVEMENT TIME AS A FUNCTION OF INDEX OF DIFFICULTY FOR DIRECT MANUAL MOVEMENT

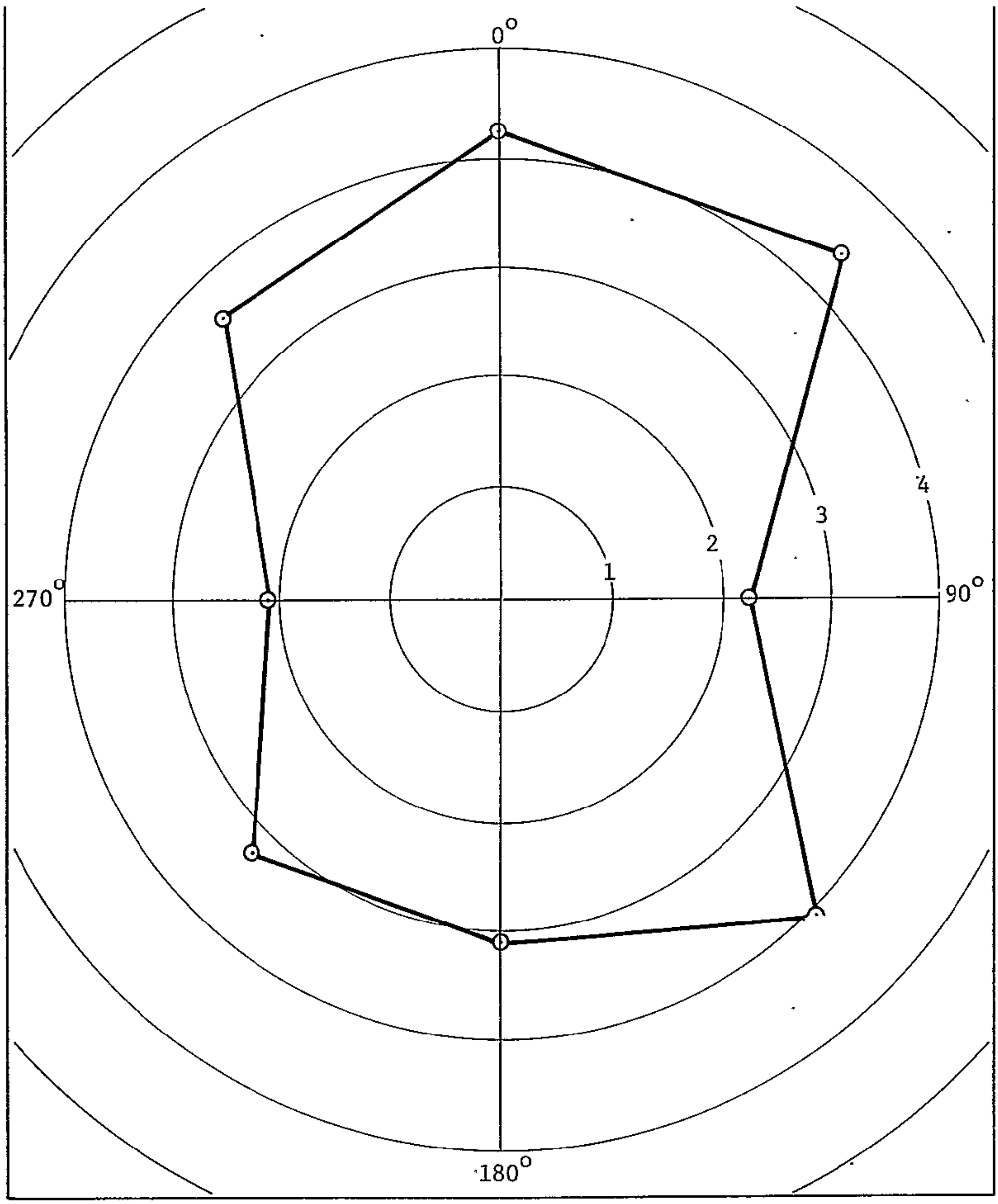

FIGURE 5-17. RATIO OF RAM/TPC MEAN MOVEMENT TIME TO ESAM/ANALOG MEAN MOVEMENT TIME

were collected using two channel TV systems as discussed in section 2. The tasks employed were also different. The present task required a single fine positioning movement where Vertut's tasks included assembly of a test object. The data would be comparable if hand times and manipulator times increased in proportion with task complexity. There are insufficient data to reach a conclusion on this issue.

The difference in terms of using a video system also impacts the manipulator time to hand time ratios reported here since subjects used direct viewing during the hand time tests. The use of video as the feedback link would be expected to contribute at least a portion of the fairly large manipulator/hand ratios reported here.

Table 5-4 also contains the estimated information processing rates for the manipulator systems under motion directions yielding significant correlations between index of difficulty and movement time. These rates are presented directly and in terms of the ratio of the hand processing rate (9.71 bits per second) to the manipulator system processing rate. In all cases, processing rates are calculated from the inverse of the slope of the regression line relating movement time to index of difficulty.

To permit comparison of time ratios between manipulator systems, the ratio of mean movement time for the RAM/TPC system to that for the ESAM/ANALOG system was obtained for each movement direction. These results are depicted in Figure 5-17. This ratio varied from a minimum of 2.1 for the 270 degree motion direction to a maximum of 4.4 for 45 degree motion. The general increase in this ratio for vertical motion and decrease for horizontal motion has been noted previously.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The results of the minimum position change test with the RAM/TPC and ESAM/ANALOG data have been extensively analyzed to assess the utility of the index of difficulty as a predictor of performance time for tasks performed by manipulator systems and to provide baseline performance data for the two systems.

Within the constraints of the test and procedure used here, the ESAM/ANALOG system was able to perform the task in significantly less time than did the RAM/TPC system. While this difference varied with direction, amplitude and final tolerance of movement, it generally exceeded a factor of two in terms of mean time ratio. The factors which might account for this effect include at least:

- Number of degrees of freedom
- Number of degrees of freedom which must be simultaneously controlled
- Resolved rate vs. direct joint control
- Controller differences
- Input-output compatibility

Number of Joints - The two systems investigated differ in terms of the number of degrees of freedom designed and built into the arm. While it is obviously necessary for the manipulator tip to be controlled in six degrees of freedom, This is effected through six joints in the case of the RAM/TPC system and through four joints plus one extension in the case of the ESAM/ANALOG system. Thus the number of parameters (degree of freedom positions) directly under the operator's control varies between the systems. Most research on human operator manual control has been devoted to single axis tracking tasks. The evidence from the multiple axis tasks which have been studied suggests that controlling more than three degrees of freedom at once is extremely difficult. It is doubtful that operators can exert continuous control over more than one axis. In multiple axis tasks, the separate axes are attended to on a time-sharing basis with discrete sampling of the various axes depending on error probability, criticality, etc. The systems studied in the current investigation vary in terms of total degrees of freedom and in terms of the degree to which the control systems permit or facilitate a discrete "sample and correct" strategy on the part of the operator.

In connection with the difference between degrees of freedom of the two manipulators, the conclusion that a five-degree system will out perform a six-degree system in general based on the current movement time data would be premature. For the current task in which the work is fairly optimally located near the centroid of the reach envelope, the ESAM/ANALOG system shows significantly superior performance in comparison with the RAM/TPC system. It has been suggested that the reduced complexity of the operator's control task due to the fewer degrees of freedom of the former system may be related to the observed performance difference. The additional degree of freedom of the RAM/TPC system, however, would provide it with greater flexibility in reaching positions within its own reach envelope. The less complex structure of the ESAM/ANALOG system, while facilitating performance in the present task might suffer by comparison in tasks requiring flexibility of reach. This implies a trade-off between number of degrees of freedom and simplification of the control task.

<u>Number of Degrees of Freedom Which Must be Simultaneously Controlled</u> - In addition to the number of degrees of freedom inherent in the manipulators, the control schemes differ in terms of the relationships between manipulator joints and controller degrees of freedom. The ESAM/ANALOG system utilizes brakes which immobilize the joints in the absence of control commands. Further, with practice on the system, operators become able to input commands

to one or two joints at a time leaving the remainder fixed. This mode is closely related to the sampling strategy discussed previously. This independence of joint control permits the operator, for example, to "aim" the entire ESAM assembly at the target via azimuth and elevation commands, the rest of the joints being ignored during this operation. The azimuth and elevation joints do not have to be coordinated. Given approximate orientation at the shoulder, the extension degree of freedom can be actuated, the other four joints remaining fixed during extension. Following extension, the fine positioning required by the present task can be effected by wrist pitch and roll if the initial aiming operation provides sufficient accuracy. If additional aiming from the shoulder joints is required, it can be provided in an iteration of the sequence described thus far. The ESAM/ANALOG system thus provides a considerable degree of independent single joint control.

By contrast, the RAM/TPC system is less amenable to a discrete sampling and independent correction strategy. The control system presently implemented regards controller outputs as specifying a manipulator tip position. Because the resolved rate control law calculates a set of joint angles satisfying the tip position command, the instantaneous tip position is a function of all the instantaneous joint angles. This reduces the extent to which the operator can independently control the separate degrees of freedom composing the tip position. That is, it is difficult for the operator to effect a pure X-axis extension, for example, while ignoring other motions. Due to the nature of the controller, further correlations between the manipulator tip motion occur. The fact that the TPC provides five outputs precludes a pure Z-axis translation in the present configuration. Translations in the vertical arc effected by a combination of other degrees of freedom. The controller itself was voted by the operators to yield inadvertent cross-coupling. Command of individual and independent components of tip position was a difficult task. This appears to be partly due to interactions between the controller and band structures and constraints and partly due to the nearly frictionless nature of the controller bearings. Operators reported that attempts to produce single axis commands-such as pure W extension generally resulted in cross coupling and consequent generation of unwanted commands.

Input-Output Compatibility

The fact that the capability of operators to independently generate single axis commands when using the ESAM/ANALOG system has been related to the fact that a more nearly one-to-one relationship exists in the ESAM/ANALOG case between controller degrees of freedom and manipulator motions than in the case of the RAM/TPC system. This does not necessarily imply that substitution of direct joint control would result in RAM performance gains. Much of the motivation for the use of the resolved rate system comes from the lack of compatibilities from the operator's viewpoint between tip motion and joint commands. Pure translation of the tip would require coordinated commands to at least two joints. The resolved rate system, in theory, generates these commands based on a pure translation command by the operator. The most promising course of action in modification of both systems would appear to include:

- Modification of the friction of the TPC bearings plus possible increase in dead band to reduce cross coupling.
- Substitution of a six degree of freedom controller to provide commands to the RAM resolved rate control system.
- Separation of RAM joint commands into two independent sets of motions controlled by separate controllers or joysticks. The separate sets should be wrist translation and orientation downstream from the wrist. This should permit much the same control strategy as was employed with the ESAM/ANALOG system.

- Utilization of the modified TPC to provide inputs to ESAM. The campatibility between ESAM joints and TPC degrees of freedom appears to be promising. This would also permit evaluation of the separate effects of manipulator configuration and controller types.

- Detailed investigation of RAM joint time histories for those movement cases identified in section 5.0 as producing random variations in movement time.

With regard to Figure 2-1, the immediate evaluation steps warranted by the present results appear to be testing of the ESAM/ANALOG system via the dexterity test. The RAM/TPC system should be modified in a selected number of modes based on the above conclusions and re-evaluated under the worst case conditions of the minimum position change test.

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