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MANIPULATOR SYSTEM MAN-MACHINE INTERFACE EVALUATION PROGRAM

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TABLE OF CONTENTS

TABLE OF CONTENTS, Continued

FIGURES AND TABLES

TABLE OF CONTENTS, Continued

1.0 INTRODUCTION

1.1 Background

In April of 1970 the then Acting Administrator of NASA, Dr. George M. Low, requested that a task team be established within NASA to investigate the applications and requirements for remote manipulator systems for future space missions. The task team, chaired by Dr. Stanley Deutsch, Chief of the Bioengineering Division, Office of Life Sciences, presented the results of its investigation to Dr. Low and his staff in October 1970. As a result of that presentation, and additional briefings to the NASA Associate Administrator, the remote manipulator system technology area was incorporated into the already existing NASA EVA committee to form the RMS/EVA committee. This committee is chaired by Dr. Deutsch and includes representatives of NASA HQ and centers involved in RMS or EVA technology development, as well as invited guests from appropriate research and development elements of the Army, Navy, and Air Force.

The RMS/EVA committee allocated responsibilities for RMS technology development to NASA centers as follows:

MSFC - Overall responsibility for earth orbital teleoperator technology integration, and specific responsibility for technology as applied to free flying systems and manipulator systems mounted internally to spacecraft.

JSC - Responsibility for development of the shuttle attached manipulator system.

ARC - Responsibility for RMS advanced technology development.

JPL - Responsibility for lunar and planetary RMS technology.

The initial activity accomplished by MSFC under this charter was the genera-tion of a Technology Development Plan for earth orbital teleoperator applicatio-The applications of particular interest included spacecraft retrieval and on-or servicing. The plan defined and described the work to be accomplished to develop, integrate, and evaluate teleoperator systems and subsystems concepts and design criteria as applied to requirements and constraints associated with these missions.

1.2 Manipulator Evaluation Program Description

In the implementation of the Teleoperator Technology Development Plan, MSFC established the Manipulator System Evaluation Program.

The major experimental effort in support of this program is being carried out in the NASA/MSFC Manipulator System Evaluation Laboratory which is housed in the Astrionics Laboratory. Additional work is being conducted in the proce engineering facilities at MSFC. Together, these facilities offer the opportun to conduct appropriate experimental investigations into human performance util zing a wide range of state-of-the-art remote manipulating systems. As in the evaluation of the visual systems, the evaluation of the manipulator systems represents part of the extensive effort undertaken to study the effect of various system parameters on operator performance of tasks necessary for remotely manned missions.

The initial testing activity involves the evaluation of existing manipula controller combinations on a set of standardized tests. The objectives for te tests utilizing various candidate controllers and manipulators are briefly given as follows:

1) Terminal Kit Adaptor - The objective of this test will be to gather time and accuracy measures for tool assisted tasks. A Rancho Los Amigos TKA end effector will be utilized in wire cutting and strippin tasks.

2) Minimum Position Change - The objective of this test will be to determine the human operator performance and controller-manipulator capabilities in making small changes in effector tip position.

3) Cargo Module Removal/Replacement - The objective of this test will be to determine the human operator performance capabilities using alternate controller-manipulator configurations to perform module removal/replacement and cargo transfer.

4) Manipulator Tip Position Accuracy - The objective of this investigati will be to determine human operator performance in achieving and holding a designated manipulator tip position for 15 seconds.

5) Manipulator Tip Position Orientation - The objective of this test will be to determine the human operator/manipulator system ability to acquire and hold a designated tip orientation with respect to a work surface.

6) Manipulator Dexterity - The objective of this test will be to determi human operator/manipulator system performance in carrying out fine positioning of varying sizes of objects.

7) Fastener Connect/Disconnect - The objective of this experiment will be to determine human operator performance and alternate manipulator configuration capabilities in operating a range of standard fasteners

8) Distance Estimation in a Dynamic Field - The objective of this experiment will be to determine the effects of video system parameters and manipulator movement on the human operator's capability to judge separation distance and to carry out separation tasks.

9) Manipulator Force-Torque Application - The objective of this experime will be to determine forces and torques applied in specified axes as the operator attempts to use selected controller-manipulator systems to position an object along one axis. Positioning will require a target or nominal force-torque. Force/torque in other axes, or excessive force/torque along the task axis constitute error.

10) Remote Antenna Deploy - The objective of this task will be to determi human operator performance and the capability of selected controller-manipulator systems in antenna deployment operations.

It is anticipated that the manipulator system evaluations will yield critical data on human performance and on the performance capability of select manipulator and controller subsystems. The tests have been formulated with th results of previous visual system evaluations in hand such that the effects of particular visual system parameters are already known, and thus controller-manipulator system effects can be determined.

Figure 1 shows the general laboratory layout. A detailed description of the laboratory equipment can be found in Section 3.0.

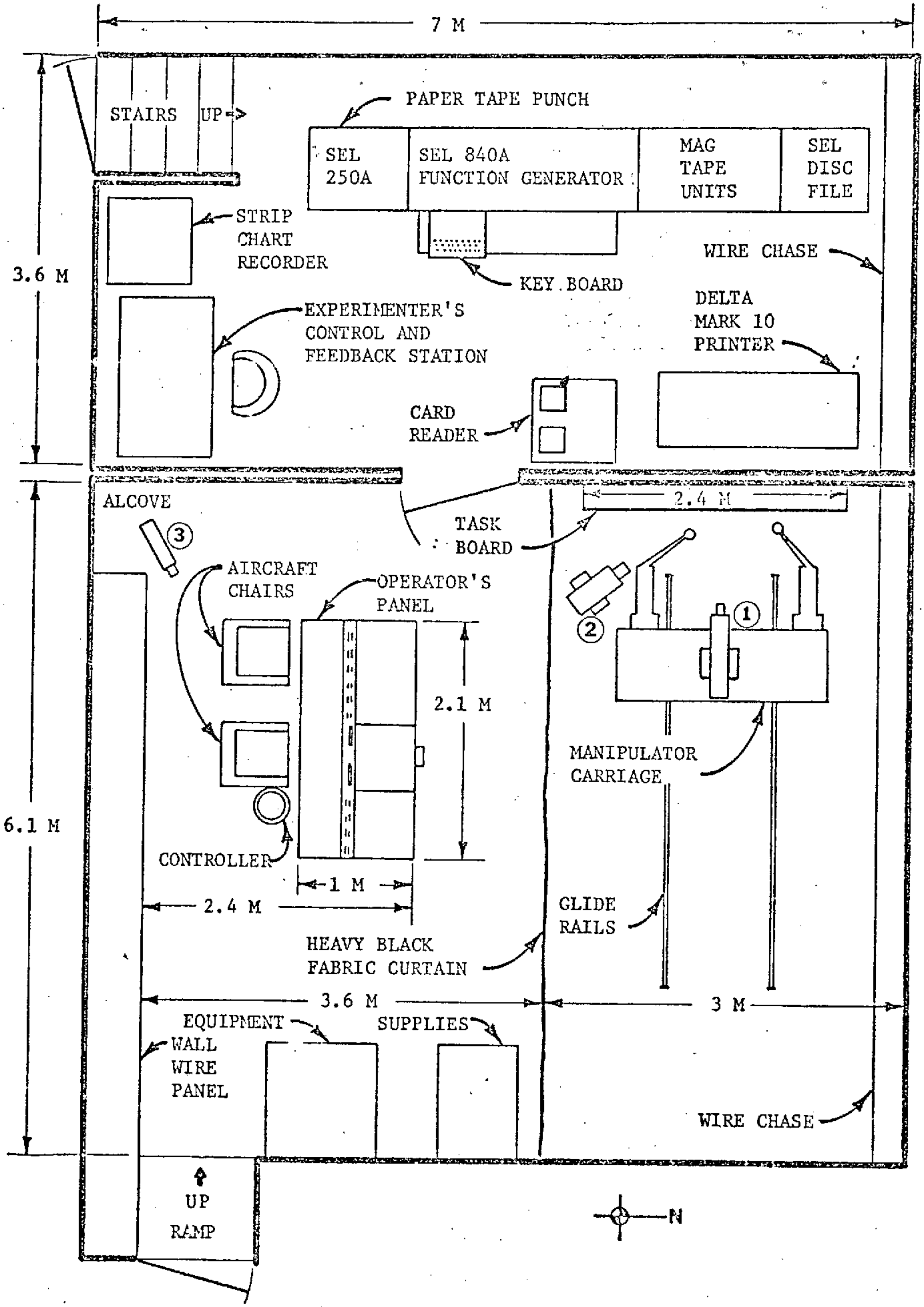


FIGURE 1. Manipulator System Evaluation Laboratory

Table 1 presents the Manipulator System Laboratory event schedule for any of the candidate tests.

TABLE 1. EVENT SCHEDULE

I. Manipulator System Laboratory

A. General Event Schedule

1. Appropriate task module placed on the task board and the hard wire leads connected to the readout and recording devices.

2. Lighting at the task site is set and calibrated.

3. Video links activated:

   a. Experimenter's view of subject
   b. Experimenter's view of a repeat of the task area
   c. Subject's view of the task site with controls for:
      i. FOV - zoom control - variable
      ii. Pan and tilt controls - variable
      iii. Focus control - variable
      iv. Iris and sensitivity setting - fixed

4. Controller activated:

   a. Limit indicators for each manipulator degree of freedom at subject's station
   b. "Bundled" limit indicator at experimenter's station indicating some one D.O.F. is at its limit

5. Computer activated for both control and recording.

6. Subject seated, chair adjusted, controller adjusted and instructions read.

7. Technician on station in task area.

8. Computer manned.

9. Experimenter's station manned.

B. Task Area

1. Lighting -- Available studio lighting will be fixed by the experimenter before test. Provisions for adjusting light levels are made.
2. 2 cameras are available and they will be set up and calibrated by experimenter before testing.

3. A Research Technician who will have voice communication with experimenter will be stationed in the Task Area to do on-site recording.

4. Position of the manipulator support structure will be fixed by the experimenter before testing.

5. Task boards will be fitted by the Research Technician prior to testing.

C. Subject's Area

1. Controller

a. Computer assisted controllers:
   i. Tie line to computer
   ii. Line interrupt at experimenter's console -- as failsafe for ARMS

All controller functions are to be handled at the subject's station, except master initiate/interrupt (located at experimenter's station).

b. All access to subject's area should be controlled so that there is no interruption during a test run.

c. Experimenter will monitor subject through a closed circuit TV system (3) located in subject's area. FOV should cover all operational areas of C/D panel.

d. Subject station and control area should accomodate 1 subject for all tests and controller position should be fixed in place, but with some (chair) provisions for accomodating individual subjects.

2. TV

a. Monitor One -- Fixed position camera (center)
   i. Pan and Tilt controls
   ii. Zoom and Focus controls

b. Monitor Two -- Mobil position camera (right)
   i. Pan and Tilt controls
   ii. Zoom and Focus controls

c. Subject will view both cameras on 2 monitors located at control panel. He will have a switch to select either view for the larger, overhead monitor. He may activate Pan, Tilt, Zoom & Foxus controls only. -- Sensitivity and iris controls will remain inactive for the subject.

d. Light settings will remain control variables and will be set by the experimenter.

e. Subject's monitor activation will be by a control switch at the experimenter's station.

C. Experimenter's Area

1. Experimenter will have a master interrupt for subject's TV & controller.

2. Voice communication to subject's area and to technician.

3. Experimenter will have a repeat of the subject's monitor plus an inset of camera 3.

4. Experimenter will have an indicator light which shows that any one manipulator joint is approaching limits for force or torque.

5. Experimenter will have a master switch to key computer to the start and stop of a test run and trial.

2.0 MANIPULATOR SYSTEM EVALUATION CRITERIA

On March 30, 1973 representatives of MSFC, JPL, and JSC met in Houston, Texas to discuss manipulator system evaluation criteria and methodology. The objective of this meeting was to pursue standardization of evaluation criteria across RMS evaluations conducted at the different centers. The MSFC preliminary description of evaluation criteria, which had earlier been presented to the RMS/EVA committee meeting in September 1972, was used as the basis for discussion in this March meeting. This report describes the updated RMS evaluation criteria agreed to by center representatives at the meeting.

2.1 Objectives and Scope of the Evaluation Criteria Development Effort

Before describing the objectives of evaluation criteria development, the objectives of performance evaluation must be established. Performance evaluation is conducted to accomplish the following:

- To determine the operational and engineering feasibility of a system concept.
- To determine the degree to which a concept satisfies specific mission requirements within the limitations imposed by mission constraints.
- To facilitate the identification of problem areas with a specific design approach.
- To provide the basis for selection of one design approach from a series of candidate concepts.

With these objectives of performance evaluation in mind, the objectives of the effort to develop evaluation criteria include the following:

- To develop standardized criteria for evaluating the engineering design and performance of RMS concepts and for establishing the relative effectiveness of competing system design concepts.

- To develop performance measures and experimental conditions to be investigated in performance evaluations.

- To develop a standard methodology for analysis and empirical evaluation of system performance.

The criteria therefore comprise the measures of system performance as well as engineering aspects of the system and environmental and operational conditions which affect system performance. The scope of the effort to develop evaluation criteria was to identify all performance measures and factors potentially affecting performance of the system as applied specifically to spacecraft retrieval and servicing missions. Based on this listing of criteria, a set of standard performance evaluation tests was then developed which were appropriate to evaluation of the manipulator subsystem of the RMS.

2.2 Evaluation Criteria - Definitions and Discussion

Definition of Terms

The role of evaluation criteria in a system design and evaluation cycle is illustrated in Figure 2. As indicated in this figure, the performance evaluation criteria development step receives inputs from system performance requirements and mission/system constraints, and the criteria are updated based on performance data obtained in evaluation tests. The criteria themselves are input to the performance evaluation and verification tests. The criteria thus form a focal position between performance requirements and constraints and analytical and empirical performance evaluation. To clarify the relationships depicted among the blocks presented in Figure 2, a definition of terms is required. For purposes of RMS performance evaluation, the following designations have been adopted:

Performance requirements - The capabilities, and levels of capability, which the system must possess to meet its specific objectives. They define what the system must do.

Performance constraints - Factors which delimit the performance capability of the system as a function of human operator and state-of-the-art technology limitations.

Performance measures - The observable, measurable indicators of the level of system performance capability. They define what the conceptual system can do.

Evaluation criteria - The factors and dimensions of performance against which measured system and subsystem performance is compared and evaluated.

- They include system parameters, figures of merit, performance parameters, and dimensions of performance capability.
- They are derived from performance requirements and constraints and they comprise the basis for performance measures and test conditions.

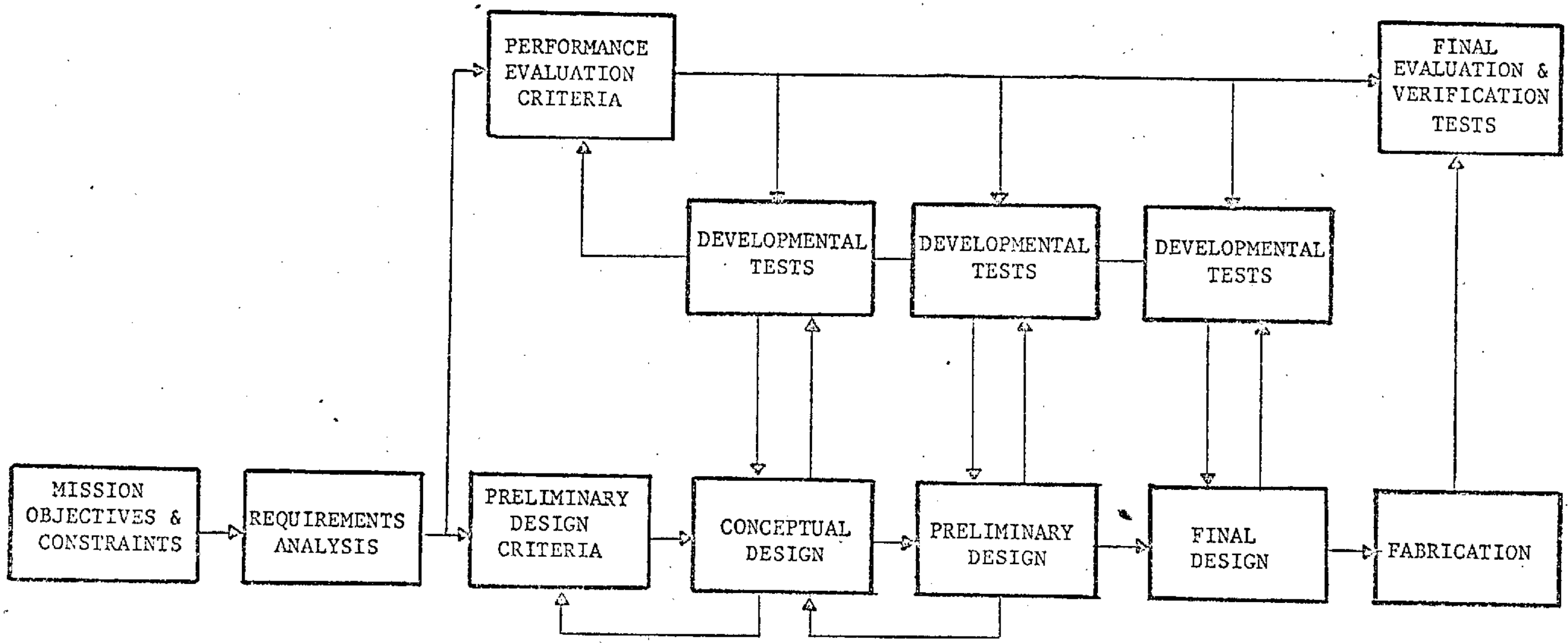


FIGURE 2. Role of Evaluation Criteria in the System Design and Development Cycle

Performance parameters - Factors indicating levels of performance capability; they lead to performance measures.

System Parameters - Factors in the real world situation which directly affect system performance capability; they lead to the evaluation conditions (physical and operational environment, design characteristics of system and subsystem hardware, etc.)

Design Criteria - The system parameters or figures of merit expressed as design specifications.

- Like evaluation criteria, they are derived from performance requirements and constraints.
- Unlike evaluation criteria, they serve as the basis for system design and do not include the conditions of performance.
- They are developed from analytical comparisons and tradeoffs and from the outputs of empirical evaluation efforts.

Evaluation criteria are therefore expressed in terms of the system performance parameters to be evaluated, and the conditions under which the evaluation is to be conducted. Evaluation conditions refer to:

- The task - procedures, sequences, and techniques.
- The hardware-software configurations (worksite, target, subsystems, etc.) and parameters of the system/system.
- System dynamics and responses.
- The environment to be represented in the evaluation.
  - physical environment
    light levels
    noise levels
    gravity conditions
    work space
  - operational environment
    operator workload
    time criticality of tasks
    operational sequences
    requirements for other activities
- Spatial and temporal relationships among objects in the environment.

- position
- orientations
- rates and accelerations
- temporal dependencies

Evaluation criteria are used in two ways: 1) in the analysis of performance capability of a system concept; and 2) in empirical investigations of system performance capability. In the analytical usage, the criteria are used to identify problem areas in a given system concept, and in tradeoffs of candidate system concepts. In the empirical tests, evaluation criteria are used to support analytic assessments, to derive objective measures of system performance capability, and to acquire measures of the limits of human performance and technology.

Evaluation criteria are of two general classes: those which enable evaluation of the performance capability of the total system; and those which are concerned with the performance of specific subsystems. The RMS subsystems of interest in this latter class include:

- manipulator configuration and structures
- manipulator actuator subsystem
- end effector subsystem
- manipulator control and controllers
- visual subsystem
- non-visual sensor subsystem
- man-machine interface
- worksite subsystem
- mobility subsystem

2.3 Evaluation Philosophy

In the planning of an empirical evaluation of an RMS system or subsystem concept, the overriding goals are to develop an experiment design which will assure maximum data reliability and validity. Reliability of data is a measure of the consistency or repeatability of the obtained data. It varies as an inverse function of the degree of experimental and sampling error present in the data. A high degree of data reliability requires rigid control of experimental conditions, and it indicates the degree to which variability in performance is true variance (as opposed to error), and hence enables prediction of the limits of system or subsystem performance capability in the operational situation.

Data validity, on the other hand, indicates the degree to which the evaluation measures what it was designed to measure. It varies as a direct function of the degree of fidelity of experimental conditions to those encountered in the operational subsystem. A high degree of data validity requires that test conditions be presentative of the range of conditions expected in the operational situation. While validity can only be assured by comparing test performance results with data obtained in the operational situation, it can be approximated by correlating the results of different evaluation programs.

Experiment design entails the application of procedures to ensure maximum experimental control and fidelity, and hence data reliability and validity. In the design of experiments, three types of variables must be considered. These include:

Dependent variables, or measures of performance.

Independent variables, or conditions to be systematically varied to determine their impact on performance.

Control variables, or conditions to be controlled such that their effect on performance is uniform and invarient.

The steps to be taken to develop an experimental design to maximize the reliability and validity of data obtained in performance evaluations are as follows:

- Clearly and concisely identify test objectives.
- Assess system performance requirements associated with functions to be evaluated.
- Establish evaluation criteria:
  - Parameters to be investigated - system and performance.
  - Range of conditions to be sampled.
- Specify the minimal levels of fidelity of the experimental situation to the real world situation, and identify the effects of failure to meet these levels.
- Identify conditions to be systematically varied and controlled (independent variables) and those to be only controlled (control variables).
- Assess effects of failure to apply rigid control over all conditions.
- Identify performance measures (dependent variables) to be evaluated.
- Develop specifications for mockups, software, procedures, and experimental control.
- Identify methods of acquiring data on performance measures and on experimental conditions during the test.
- Identify statistical analyses to be used to assess system performance in terms of performance measures and as a function of experimental conditions.
- Develop a checklist for assessing degree of control and of fidelity of the experimental situation once mockups, equations of motion, procedures, etc., are completed and implemented prior to testing.

2.4 Derivation of RMS Evaluation Criteria

As stated in the previous section, evaluation criteria are composed of system and performance parameters. System parameters comprise system and environmental factors which directly impact the performance of the system. Performance parameters indicate the dimensions along which system performance is measured.

Evaluation criteria are derived from mission and system requirements and constraints. Requirements include functional requirements or operations which must be performed, and performance requirements or levels of performance which the system must achieve. Functional requirements are derived from an operational analysis of the specific mission, and include the functions and tasks to be accomplished by the system in conducting the mission. Performance requirements relate to specified levels of performance for a particular mission.

The steps involved in developing evaluation criteria are as follows:

1) Identify mission requirements and constraints.
2) Analyze system function and tasks.
3) Identify performance requirements associated with each function.
4) Identify performance parameters - dimensions of performance.
5) Identify system parameters - factors which influence performance.
6) Identify engineering parameters.

These steps were accomplished for the spacecraft servicing (module removal/replacement) and retrieval missions insofar as mission operations were identifiable. From mission operations, system functions and tasks were identified. For each task, the parameters - of the system and of performance - were identified for each subsystem. The RMS subsystems involved in each task of the spacecraft servicing and retrieval missions are identified in Tables 1 and 2 respectively. Parameters are identified by subsystem and task in

Tables 2-11. The complete list of parameters for each subsystem is presented in Appendix A. The purpose of this list is to indicate the factors which must be considered in an evaluation, either as dependent variables, independent variables, or control variables.

The listing of system and engineering parameters as evaluation criteria cannot be exhaustive since the identification of conditions to be evaluated and controlled depends in large part on the objectives of specific tests. The general types of conditions to be incorporated in systems and subsystems evaluations include the following:

System Criteria

- The task to be performed and associated performance requirements and constraints.
- The design concept for the teleoperator system and appropriate subsystems (including the worksite).
- The design concept for other system hardware associated with the task (e.g., satellites to be retrieved).
- Physical environment conditions levels of which are judged to have differential effects on the performance capability of the total system and individual subsystems (lighting, gravity, absence of visual reference cues, etc.).
- Operational environment conditions levels of which are judged to have differential effects on performance capability (workload, number of operators, time constraints, etc.).
- Spatial and temporal relationships of objects in the environment (relative positions, rates, accelerations, orientations, etc.).
- System and target dynamics and responses (spin rates, equations of motion, response lags, etc.).
- Sensor and control system errors, drifts, misalignments, etc. expected in the real world situation.

Subsystem Criteria

- Manipulator configuration and structures and actuator subsystem

    - Degrees of freedom and angles and rates of each
    - Conditions of loading
    - Conditions of reach
    - Spatial relationship of manipulator base to worksite
    - Sensor-manipulator integration
    - Actuator design concepts

- End effector subsystem

    - End effector design
    - Sensor integration
    - Spatial relationship to worksite
    - Alignment and grasp tolerances - clearance
    - Rate, direction, and period of attach point motion to be tracked

- Manipulator control and controllers

    - Controller design
    - Control system design
    - Conditions of reach
    - Range of manipulator rates required
    - Gravity conditions on operator
    - Suit conditions
    - Orientation of operator body coordinates to worksite coordinates

- Visual subsystem

    - Visibility conditions:
      illumination levels
      distance to target
      alternate viewing aspects - orientations
      spatial relationships of target, sun, moon, earth

    - Transmission conditions:
      signal-noise levels
      signal digitization
      band limiting

    - Target conditions:
      sizes
      shapes
      motions and rates
      configuration

- Video design conditions:
  camera locations
  field of view
  frame rate, etc.

- Video aid conditions:
  availability
  degree to which modifications are feasible
  aid design

• Non-Visual Sensor System

  - Applied forces
  - Reflected forces
  - Force gradients
  - Textures and contours to be identified
  - Range and rates with respect to the target
  - Star field conditions - for orientation and navigation

• Man-Machine Interface

  - Levels of workload, nominal and contingency
  - Levels of skills
  - Alternate operating procedures and techniques
  - Information displayed
  - Degree of pre-processing prior to display
  - Degree of display integration

• Worksite Subsystem

  - Clearances and obstructions
  - Module location, size, shape, mass
  - Attach point design - sixe, shape, number, location, etc.
  - Design of markings and aids
  - Design of fasteners, connectors, etc.

• Mobility System

  - Control system responses - handling qualities
  - Stabilization system deadbands
  - Variations in system weight as a function of design, fuel expenditure, attachment to target, etc.

TABLE 2
Teleoperator Subsystems for Module Removal/Replacement

System Function	System Task	Subsystems Involved: Visual	Manip. Config.	Manip. Actuat.	End Effect.	Manip. Control	Non-Vis. Sensor	Worksite
Prepare for Removal	Identify module	X						X
	Position for removal	X	X	X	X	X	X	X
	Inspect worksite	X						X
	Orient for removal	X	X		X	X		X
	Configure for removal	X	X	X	X	X	X	X
Module Removal	Uncover module	X	X		X	X		X
	Stow cover	X	X		X	X		X
	Remove obstacles	X	X		X	X		X
	Inspect Module	X						X
	Configure camera-lights	X						X
	Attach tether	X	X		X	X		X
	Break connections	X	X	X	X	X		X
	Stow connection	X	X		X	X		X
	Unlock module	X	X	X	X	X		X
	Grasp module	X	X	X	X	X		X
	Free module	X	X	X	X	X		X
	Retract module	X	X	X	X	X		X
	Handle module	X	X	X	X	X		X
	Stow module	X	X		X	X		X
	Detach tether	X	X		X	X		X
Module Replacement	Attach tether	X	X		X	X		X
	Retrieve module	X	X	X	X	X		X
	Inspect module	X	X			X		X
	Inspect worksite	X						X
	Orient for replacement	X	X		X	X		X
	Align module	X	X	X	X	X		X
	Install module	X	X	X	X	X		X
	Adjust module	X	X	X	X	X		X
	Make holddown	X	X	X	X	X		X

TABLE 2 (Continued)

Teleoperator Subsystems for Module Removal/Replacement

System Function	System Task	Subsystems Involved						
		Visual	Manip. Config.	Manip. Actuat.	End Effect.	Manip. Control	Non-Vis. Sensor	Worksite
Module Replacement	Unstow connections	X	X		X	X		X
	Make connections	X	X	X	X	X		X
	Detach tether	X	X		X	X		X
	Verify replacement	X	X	X	X	X		X

TABLE 3

Teleoperator Subsystems for Satellite Retrieval

	Subsystems Involved						
	Visual	Manip. Config.	Manip. Actuator	End Effect.	Manip. Control	Non-Visual Sensor	Worksite
Acquire satellite	X					X	X
Rendezvous	X					X	X
Station Keep	X					X	X
Measure dynamics	X					X	X
Inspect	X						X
Align axes	X	X	X		X		X
Identify attach point	X						X
Final closure	X	X	X		X	X	X
Detect obstacles	X					X	X
Avoid obstacles	X	X	X		X	X	X
Track attach point	X	X	X		X	X	X
Grasp attach point	X	X	X	X	X	X	X
Apply stabilization force	X	X	X	X	X	X	X
Configure for return	X	X	X	X	X	X	X
Return satellite	X	X	X	X	X	X	X
Perform safing	X	X	X	X	X	X	X
Emplace in bay	X	X	X	X	X	X	X

TABLE 4
Manipulation Subsystems-System Parameters Removal/Replacement

Task	Manipulation Configuration	Manipulation Actuation	End Effector	Worksite	Control
Positioning	Variable reach				Reach control Config. control
Configuration	Degrees of freedom	Range of motion - each df Available gains	Articulation Rate selection Time to modify		Effector - arm interface
Uncover	Reach configuration Sensor integration	Force gradients	Articulation Grip span	Cover Charac.	Reach control Effector control
Stow cover	Variable reach	Range of rates Stability-moving Time lags	Articulation Force gradients	Clearance Stow location Cover size-mass	Config. control Reach control Handling qualities
Remove obstacles	Variable reach	Force gradients	Articulation Grip span	Clearance Obstacle size - location, mass	Arm control
Attach tether	Variable reach Sensor integration	Force gradients	Articulation	Tether charac. Attachment charac.	Arm control Effector control
Break connections	Variable config.	Force gradients	Contact points Sensor interface	Connector charac.	Fine arm control Handling qualities
Unlock module	Variable config.	Force gradients	Tool interface	Lock-tool charac.	Fine arm control
Grasp module	Stability One-two arm	Rate gradients	Grip span Contact points Position indexing Sensor integ.	Attach point char.	Dual arm control Effector control
Free module	Variable config.	Force gradients	Force gradients	Attach point char.	Arm control

TABLE 4 (Continued)

Manipulation Subsystems-System Parameters Removal/Replacement

Task	Manipulation Configuration	Manipulation Actuation	End Effector	Worksite	Control
Retract module	Variable config.	Force gradients Rate gradients	Articulation Indexing Sensor interface	Attach point char. Module char. Worksite char.	Alignment control Force control
Handle module	Variable config.	Force gradients	Articulation	Same as above	Arm control
Align module	Variable config.	Rate gradients Stability	Articulation	Align Aids	Arm control
Install module	Variable reach	Force gradients	Hand orient.	Align aids	Reach control

TABLE 5
Manipulator Subsystems-System Parameters-Retrieval

Task	Manipulator Configuration	Manipulator Actuation	End Effector	Worksite	Control
Align Axes	Variable config.	Range of motion	-	Aids	Config. control
Closure	Variable reach	Rate gradients	-	Attach points char.	Handling qualities Reach control
Avoid obstacles	Variable config.	Sensor integ.	-	Obstacle char.	Config. Control
Track attach point	Variable reach	Rate gradients Stability	Articulation Avail. orient.	Dynamics	Rate control Handling qualities
Grasp attach point	Variable reach	Stability Force gradients	Sensor integ.	Dynamics	Effector Control
Apply stabilization force	Strength	Stability Force gradients	Sensor integ.	Dynamics	Force control
Configure for return	Variable config.	Rate gradients Force gradients	Grip span	Attach points	Config. control
Return satellite	Variable config.	Force gradients	Alternate config.	Attach points	Transfer control Control modes
Perform safing	Variable config.	Force gradients Rate gradients	Articulation	Attach points	Config. control
Emplace in bay	Variable reach	Rate gradients	Position index.	Aids	Reach control

TABLE 6
Manipulation Subsystems- Performance Parameters Removal/Replacement

Task	Manipulation Configuration	Manipulation Actuation	End Effector	Worksite	Control
Positioning	Config. Accuracy	Time to position	-	-	Tip position accurac
Configuration	-	Drift-stationary	Effector select.	-	Effector interface
Uncover	-	Applied force Stability Mass Handling	Grip force	Force limits	Force indexing Orient. accuracy
Stow cover	-	Stability-loaded Mass handling	Grip retention Duration of grip	-	Rate indexing Position index
Remote obstacles	Config. accuracy	Inadvertent contact	Dexterity	Force-limits	Orient. accuracy
Attach tether	-	Applied force Stability	Dexterity	-	Force indexing Position indexing Position accuracy
Break connections	-	Applied force Stability Minimum position change	Dexterity Grip retention	-	Rate accuracy Force indexing
Unlock module	-	Applied force Stability	Dexterity	-	Force indexing
Grasp module	-	Applied force Stability Deflect. force	Time to grasp Duration of grasp Grip retention	Force limits	Orient. accuracy Position accuracy
Free module	-	Applied force Energy-power	Grip retention	-	Force control Alignment

TABLE 7
Manipulator Subsystems - Performance Parameters - Retrieval

Task	Manipulator Configuration	Manipulator Actuation	End Effector	Control
Align axes	Config. accuracy	Stability Drift Align. accuracy	-	Position accuracy Orient. accuracy
Final closure	-	Rate accuracy	-	Rate control
Avoid obstacles	Config. accuracy	Reaction time Inadvertent contacts	-	Position accuracy
Track attach point	Config. accuracy	Stability Align. accuracy orient. while moving	-	Position accuracy while moving Position indexing Rate indexing
Grasp attach point	-	Deflection force Applied force Stability	Grip force	Position accuracy Force indexing
Apply stabilization force	-	Applied force Mass handling Energy-power	Grip retention	Force accuracy Time to apply
Configure for return	Config. accuracy	-	Grip retention	Config. control accuracy
Return satellite	-	Mass Handling Rate accuracy	Grip retention Duration of grasp	Rate control accuracy
Perform safing	-	Applied force Stability	Dexterity	Force accuracy Position accuracy Time to perform
Emplace in bay	Configur. accuracy	Rate accuracy	Grip retention	Rate control accura Time to perform

TABLE 8

VISUAL - SENSOR - DISPLAY SUBSYSTEMS - SYSTEM PARAMETERS - REMOVAL/REPLACEMENT

Task	Visual	Worksite	Non-Visual Sensor	Display
Identify module	resolution field of view lighting	markings contrast reflectivity	-	location contrast
Position for removal	aspect	align. aids	-	
Inspect site	field of view lighting aspect	markings reflectivity anomalies		size location
orient	camera control	configuration	Position	degree integration
uncover module	contrast	markings	force feedback	integration
stow cover	depth of view camera control	markings reflectivity	force	size
remove obstacles	field of view depth of view aspect	coding pattern of obstacles	contact	integration aid
inspect module	resolution lighting aspect	markings	-	size location
Configure camera lights	pan-tilt zoom direction of view number of views light intensity light direction	-	-	feedback
Attach tether break connection stow connection unlock module	resolution aspect field of view transmission characteristics	markings	force	integration
grasp module	depth of view	markings	contact	feedback aids
retract module	aspect	markings	force	feedback
install module				no. of views Align. Aids

TABLE 9

VISUAL - SENSOR - DISPLAY SUBSYSTEMS - SYSTEM PARAMETERS - RETRIEVAL

Task	Visual	Worksite	Non-Visual Sensor	Display
Acquire satellite	field of view	beacon	ranging sensor chacteristics	target detection
	resolution	characteristics		
Rendezvous	field of view	same as above	same as above	display aids
Station Keep	resolution	markings	same as above	display aids
	magnification			
measure dynamics	motion resolution	dynamics	dynamic sensor characteristics	aids
	depth of view			
	frame rate			
Inspect	resolution	contrast		
	transmission characteristics	reflectivity	-	number of views
	lighting			
	aspect			
Align axes	motion	dynamics	-	aids
	resolution			
Identify attach point	resolution	contrast	-	aids
	lighting	markings		
final closure	depth of view	attach point	ranging	aids
	motion resolution	characteristics		
detect obstacles	grey scale	obstacle	tactile	sensor
	field of view	pattern	sensor characteristics	integration
Avoid obstacles	same as above	same as above	-	-
Track attach point	frame rate			
	motion resolution	dynamics	track sensor	aids
grasp attach point	aspect	point character.	force-contact	integration
Apply force	motion resolution	dynamics	force	integration
Configure for return	field of view	attach points	ranging	aids
return satellite	field of view	beacon	ranging	aids
	resolution			
perform safing	resolution	attach point	force	number
	frame rate			
emplace in bay	field of view	markings	force alignment	aids
	aspect			

TABLE 10

VISUAL - SENSOR - DISPLAY SUBSYSTEM- PERFORMANCE PARAMETERS - REMOVAL/REPLACEMENT

Task	Visual	Worksite	Non-Visual Sensor	Display	Operator
Identify module	Accuracy	-	-	-	Acuity form persep. spatial orient.
Positioning	alignment acc- uracy	-	-	-	
Inspect site	anomaly detection	-	-	-	Pattern recog. brightness discrimination spatial orient.
Orient for removal	accuracy	-	-	-	
Uncover module	-	-	-	-	size discrim. form percep. errors
stow cover	-	-	-	-	
Remove obstacles	-	- -	- -	- -	
inspect module	anomaly detection	-	-	-	Pattern recog. form percep. time to detect acuity
Configure camera, lights	accuracy	-	-	-	Pattern recog. size discrim. procedures
Attach tether break connections stow connections unlock module grasp module	Accuracy Time	-	sensor lags	response time	Acuity form perception depth perception spatial orient.
			accuracy of contact sensing	response time	depth perception alignment percep.
retract - install module	-	-	accuracy of force sensory	response time	depth percep. alignment

TABLE 11

VISUAL - SENSOR - DISPLAY SUBSYSTEM - PERFORMANCE PARAMETERS - RETRIEVAL

Task	Visual	Worksite	Non-Visual Sensor	Display	Operator
Acquire satellite	accuracy detection range	-	ranging accuracy	-	Acuity
Rendezvous Station Keep	-	-	ranging	-	rate estimation
measure dynamics	-	-	accuracy	-	rate estimation spatial orient.
Inspection	-	-	-	response time	acuity brightness discr. pattern recognition
Align axes	-	-	-	-	align accuracy
Identify attach point	-	-	-	-	accuracy acuity
final closure	-	-	ranging accuracy	-	depth perception rate estimation
detect - avoid obstacles	accuracy	-	accuracy	time to respond	Pattern recog. depth perception
track attach points	alignment accuracy	-	sensor accuracy	response time	form perception motion perception
grasp attach point	-	-	force sensing accuracy	response time	alignment accuracy depth percep. rate estimation
apply Stabiliz. force	-	-	force sensing accuracy	time to respond	rate estimation
Configure for return	-	-	-	-	form percep.
return	-	-	ranging	-	rate estimation
perform safing	-	-	-	-	Pattern recog. acuity depth perception
emplace in bay	-	-	contact sensing accuracy	response time	acuity rate estimation depth perception

2.5 Development of Standardized Tests for Manipulator Subsystem Evaluation - Satellite Servicing

From an assessment of the performance parameters associated with the manipulator configuration, actuator, end effector, and control subsystems (in Appendix A), it is evident that a listing of evaluation measures would include factors classified along at least three dimensions: time, accuracy, and energy. Performance parameters related to each class, from Appendix A, would include:

Accuracy Measures:

- Tip placement accuracy
- Tip orientation accuracy
- Alignment accuracy
- Manipulator configuration accuracy
- Dexterity
- Grip retention accuracy
- Ranging accuracy
- Obstacle detection
- Operator visual performance accuracy
- Rate control accuracy

Time Measures:

- Time to detect
- Time to respond
- Time to perform

Energy Measures:

- Force application
- Power expenditure
- Operator workload

A series of manipulator system tests were developed to obtain data on these performance parameters. The actual identification of standardized tests is based on the following steps:

1) Define test program guidelines and constraints:

- Coverage - tests produce data relevant to the assessment of concept or system effectiveness in satisfying all important mission and system requirements.

- Number of tests - minimum number which will satisfy the coverage criteria.

- Degree of specificity of tests to individual requirements - integration of requirements within specific tests to the level necessary to study relationships among requirements.

- Data quality - maximize data reliability (through experimental control), data validity (through apparatus fidelity), and data applicability (through selection of measures and variables).

- Test economy - low cost (time and material) test setup within limits of data reliability and validity criteria.

2) Determine type of tests required:

- Functional (from functional and performance requirements) vs. structural (from engineering requirements based on performance requirements).

- Elemental or molecular (directed at assessing a specific system requirement) vs. compound or molar (requiring investigation of the relationships among several system requirements).

3) Identify specific tests by type:

- From assessment of test requirements generated in the system development cycle (Figure 2).

- From assessment of required dependent measures abstracted from the list of performance parameters in the system evaluation criteria (Table 12 for satellite servicing).

- Identify applicable functional requirements for functional tests (Table 13). Identify applicable engineering parameters from the system evaluation criteria for structural tests.

- Identify relationships between selected tests and the manipulator basic operations identified by E. Heer (Table 14).

4) Develop experimental design - each test:

- Review system parameters in evaluation criteria.
- Determine which parameters are of interest in terms of their differential effects on performance as measured by dependent variables. These are independent variables.
- Determine which parameters must be controlled throughout the test - these are control variables.
- Develop relationships of interest among independent variables.
- Develop test conditions and procedures.

5) Develop test plans - each test - Appendix B.

TABLE 12. RELATIONSHIPS OF PERFORMANCE MEASURES AND TESTS

MANIPULATOR PERFORMANCE MEASURES	ELEMENTAL TESTS					COMPOUND TESTS		
	TIP PLACEMENT	TIP ORIENT.	MIN. POS. CHANGE	FORCE-TORQUE AP.	DEXTERITY	ANTENNA DEPLOY	FASTENER CONNECT	MODULE REPLACEMENT
TIP PLACEMENT ACCURACY	X		X					
TIP ORIENTATION ACCURACY		X					X	X
ALIGNMENT ACCURACY		X				X		X
MANIPULATION CONFIGURATION ACCURACY						X		X
DEXTERITY					X			
GRIP RETENTION ACCURACY						X	X	X
OBSTACLE DETECTION ACCURACY								X
OPERATOR VISUAL PERFORMANCE						X	X	X
RATE CONTROL ACCURACY						X		
TIME TO PERFORM	X	X	X		X	X	X	X
FORCE APPLICATION				X		X		X
POWER EXPENDITURE				X				X
OPERATOR WORKLOAD						X		X

TABLE 13
RELATIONSHIP OF MISSION REQUREMENTS TO MANIPULATOR STANDARD TESTS

SERVICING MISSION FUNCTIONAL REQUIREMENTS	ELEMENTAL TESTS					COMPOUND TESTS		
	TIP PLACEMENT	TIP ORIENT.	MIN. POS. CHANGE	FORCE-TORQUE AP.	DEXTERITY	ANTENNA DEPLOY	FASTENER CONNECT	MODULE REPLACEMENT
OBSTACLE REMOVAL	X	X						
FASTENER DISCON-NECTING	X	X	X		X		X	
COVER REMOVAL	X			X				
TERMINAL DISCON-NECTION	X	X	X		X			X
MODULE REMOVAL	X			X	X			X
MODULE REPLACEMENT	X	X			X			
MODULE INSTALLATION	X	X						X
TERMINAL CONNECTION	X	X	X		X			X
MOTION/FORCING				X		X		X
FASTENER CONNECTING	X	X	X		X		X	
SURFACE CLEANING	X	X						
CIRCUIT TESTING	X	X	X					

TABLE 14. RELATIONSHIPS OF TESTS TO MANIPULATOR BASIC OPERATIONS

	ELEMENTAL TESTS					COMPOUND TESTS		
OPERATIONS	TIP PLACEMENT	TIP ORIENT.	MIN. POS. CHANGE	FORCE-TORQUE AP.	DEXTERITY	ANTENNA DEPLOY	FASTENER CONNECT	MODULE REPLACEMENT
GROUPING						X	X	X
MOVING				X		X	X	X
GUIDING			X		X	X	X	X
POSITIONING	X				X	X	X	X
ORIENTATION		X				X	X	X
SENSING				X		X	X	X
FORCING				X		X	X	X

3.0 MANIPULATOR SYSTEM EVALUATION LABORATORY

3.1 Introduction

The evaluation of candidate manipulator and controller systems is to be carried out at Marshall Space Flight Center's Astrionics Laboratory which houses the Manipulator System Evaluation Laboratory. It is expected that the laboratory facilities will offer both a realistic and controlled environment in which to explore the capabilities of existing man-in-control remote manipulating units. It is also anticipated that the laboratory will offer an appropriate test site for gathering data on advanced manipulator systems as the state-of-art technology advances. This document reflects the ongoing effort to develop appropriate plans for fully utilizing the MSFC facilities currently involved in manipulator research. Coordination for the development of these remote manipulator plans will be carried out under the direction of the appropriate MSFC officials.

It is the intention of the test program to integrate available material developed for controllers, manipulators, control/display arrangements, feedback systems and mission objectives in such a manner as to yield relevant data on human operator performance under several possible task conditions.

3.2 Facilities

The primary facilities for the evaluation of candidate controller/manipulator systems is located in the Astrionics Laboratory, MSFC. The detailed layout of the space is shown in Figure 1, and depicts the three major work areas.

Task Area

The task area provides an isolated location for performing tasks via remote control with candidate manipulator systems. At the west wall is a vertical task board (2.44 x 2.44 meters) which is painted a nonreflective flat black. This task board provides a surface on which to secure various task modules which represent the various individual tests. Each task module will be approximately .31 meters square and contain the appropriate task hardware such as target discs, PC boards, etc. The task modules are each described further in the test plan section.

The next item of equipment is the manipulator support cabinet which is a large (1.2 x 1.1 x .5 m) structure which supports the manipulators and associated electronic equipment on a set of glide rails. The glide rails make it possible to move the support cabinet and adapt the laboratory to a number of different manipulator systems.

The manipulator system is mounted on the front side of the cabinet, while on the top of the cabinet is mounted a Cohu model 2000 TV camera with remote pan & tilt unit. Variable camera parameters are pan, tilt, focus, field of view, iris setting & target sensitivity. This cabinet mounted camera is fixed, while a second Cohu with the same variable parameters is fitted to a moveable tripod for positioning at prescribed locations in the task area. The lighting system within the task area consists of two Colortran model 104-311-1kw studio lights which can be positioned at prescribed locations in the task area, so as not to interfere with either the manipulation system or the TV system. This west half of the task area is the principal task area as shown in Figure B-1. The east half of the area can be utilized for task module storage and for calibration and maintenance equipment, as well as offering a place for an on-site observer to watch the operations of all the hardware.

Associated cabling for system control runs from the support cabinet, under the floor, to the work site.

Subject's Station

The subject's station is represented as Area 2 in Figure B-1. It is 3.6 x 6.1 meters, and contains the control-display console and operator station. The console is 2.1 m long, 1.3 m high, and 1 m deep with a horizontal work surface 47 cm deep. The control display arrangement is separated into five major areas. To the far left of the operator is a panel for calibration equipment. This contains:

1) A Tektronix RM529 wave form monitor for calibration
2) An emergency shutdown pull switch for system power control

The second panel from the left contains: left field controls, including:

1) Left arm position and torque limit indicators
2) Left arm position and torque direction indicators
3) Left arm indicator select switch for DOF in 2 above
4) Cohu camera control unit for the fixed camera

The third panel is the one directly in front of the operator and contains the television controls and monitors for visual feedback. In addition, one large 19 in. diagonal monitor is mounted above this panel and tilted down toward the operator. This monitor provides a large screen video repeat of either the fixed (cabinet) or moveable (tripod) camera. This third panel contains:

1) Elapsed time indicators (2)
2) 2 Contac 7 in. diameter TV monitors & associated controls
3) Subject's intercom station

The fourth panel is essentially similar to panel number 2. It contains the same controls and displays for the right manipulator, and controls for the movable camera.

The fifth area is the controller itself and is generally located at the right hand of the operator next to his chair. This, however, can vary in order to accommodate significantly different classes of controllers.

Additionally, the subject's station has provisions for storage of test equipment in cabinets on the east wall, and on the west side of the subject's area there is a TV camera mounted in an alcove, which provides the experimenter with a view of the subject performing the test operations. Access to this area will be closely controlled during any experimental run to reduce the chance of operator distraction.

Experimenter's Area

The experimenter's area contains the computer support equipment for the test program, as well as the experiment recording devices and experimenter's control station. The experimenter's area is 3.6 m by 7 m and the computer support equipment includes:

1) A SEL 520A paper tape punch
2) A SEL 840A function generator
3) 2 SEL magnetic tape units
4) A SEL disc file
5) An operator's work table with input keyboard
6) A Delta Mark 10 output printer
7) A card reader

This equipment is used primarily for controller/manipulator support and for primary data collection and recording. The operation of this equipment is managed by technical staff independent of the experimenter.

The experimenter has his own control/display area which includes the following:

1) A control/display station which provides for primary stop/start commands to all other work stations. It is a master key for the entire laboratory.

2) A 19 inch diagonal TV monitor which provides for video feedback of the task site as well as an inset of a picture of the subject's station. The inset is provided by a special effects generator.

3) A strip chart recorder for secondary information which is gathered on the manipulator operations.

The entire laboratory is controlled for temperature and humidity due, in part, to the electronic components. Lighting and noise levels will be controlled for each experiment at a constant level, as yet to be determined.

APPENDIX A

Listing of Teleoperator System Evaluation Criteria

MANIPULATOR SYSTEM EVALUATION CRITERIA

Category: I. Total System Evaluation

Criteria	Levels of Criteria: Perform Parameter	Engineering Parameter	System Parameter
Time, Accuracy, Energy Expenditures for:			
Stable satellite capture	X		
Unstable satellite capture	X		
Satellite despin, decone, detumble	X		
Satellite tiedown for recovery	X		
Satellite safing	X		
Satellite handoff	X		
Satellite emplacement in cargo bay	X		
Teleoperator stabilization - worksite	X		
Satellite - cargo transfer	X		
Maintenance/repair/refurbishment	X		
Satellite systems update	X		
Teleoperator separation	X		
Teleoperator dock to shuttle	X		
Impart spin to satellite	X		
Retract P/L from bay	X		
Position orient P/L in space	X		
Transport P/L	X		
Mate modules	X		
Assembly and erection of antenna	X		
Sample plasma wake-contamination	X		
Operate /monitor experiments	X		
Emplace experiments	X		

MANIPULATOR SYSTEM EVALUATION CRITERIA

Category: I. Total System Evaluation

Criteria	Levels of Criteria: Perform Parameter	Engineering Parameter	System Parameter
Position sampling device	X		
Acquire/handle/store sample	X		
Assist EVA astronaut	X		
Inspect surfaces - assemblies	X		
Relative positions			X
Orientations			X
Rates			X
Teleoperator - dynamics			X
Physical characteristics			X
Target - dynamics			X
Physical characteristics			X
Geometric relationship			X
Earth, sun, moon, target, shuttle,			
and teleoperator			
Failure modes			X

MANIPULATOR SYSTEM EVALUATION CRITERIA

Category: II. Subsystem Criteria - Manipulator Configuration

Criteria	Levels of Criteria: Perform Parameter	Engineering Parameter	System Parameter
Number of manipulators		X	
Number of joints		X	
Degrees of freedom - each joint			X
Angle of rotation - each df (rotation)		X	X
Functional reach envelope			X
Struc./elec./mech. integration of			X
Variable Configuration			X
ARM mass-weight		X	
Mass distribution			X
Balancing			X
Material		X	
Strength - structures		X	
Hardness - structures		X	
Stowed volume		X	
Deployed volume		X	
Mechanical interfaces		X	
Electrical interfaces		X	
Structural interfaces		X	
Electro-mechanical interfaces		X	
Thermal limits		X	
Configuration accuracy	X		

MANIPULATOR SYSTEM EVALUATION CRITERIA

Category: II. Subsystem Criteria - Actuator System

Criteria	Levels of Criteria: Perform Parameter	Engineering Parameter	System Parameter
Angular or linear rates - each df		X	
Angular or linear accelerations -each df		X	
Rate gains available			X
Stability when stationary	X		X
Stability when moving	X		X
Drift when stationary	X		
Deflection forces	X		
Minimum Positional change	X		
Rate gradients available			X
Actuator time lags			X
Input-output ratios - rate response		X	
Force gradients available			X
Torque application - each joint		X	
Stall torque - each joint		X	
Smoothness of motions			X
Actuator size		X	
Actuator - Arm integration		X	
Actuator power	X	X	
Actuator reliability		X	
Orientation Accuracy - Moving	X		
Accuracy of straight line motion	X		

MANIPULATOR SYSTEM EVALUATION CRITERIA

Category: II. Subsystem Criteria - End Effector

Criteria	Levels of Criteria: Perform Parameter	Engineering Parameter	System Parameter
Number and types of available motions			X
Rates and rate gradients - each motion			X
Dexterity - small object handling	X		
Articulation - alternate configurations			X
Number of contact points			X
Force/torque gradients			X
Stall force/torque		X	
Grip size-span			X
Position indexing provisions			X
Alternate orientations available			X
Interface with manipulator			X
Struc./elec./mech. integration of			X
sensors with effector			
Grip retention accuracy	X		
Duration of grip retention	X		
Time to grasp	X		
Time to modify configuration	X		
Accuracy of Effector Selection	X		
Grip Force	X		

MANIPULATOR SYSTEM EVALUATION CRITERIA

Category: II. Subsystem Criteria - Non Visual Sensors

Criteria	Levels of Criteria: Perform Parameter	Engineering Parameter	System Parameter
Ranging - range, rate, and LOS rate			X
Range of response			X
Accuracy at range points	X		
Display characteristics			X
Force			
Gradients		X	
Input/output ratios			X
Position sensing and display			X
Rate sensing and display			X
Environment sensing and display			X
Obstacle detection and avoidance			
Contact sensors			X
Proximity sensors			X
Early warning sensors			X
Range at which obstacles are detected	X		
Detection lag	X		
Grip integrity sensing			
Dead bands			X
Accuracy	X		

MANIPULATOR SYSTEM EVALUATION CRITERIA

Category: II. Subsystem Criteria - Worksite Interface

Criteria	Levels of Criteria: Perform Parameter	Engineering Parameter	System Parameter
Attach points - hand holds			
Location			X
Clearance			X
Position indexing			X
Number			X
Impulse and sustained force limits	X		X
Modules for removal/replacement			
Accessibility			X
Connections - type			X
Connections - number			X
Connections - complexity			X
Number of modules			X
Size - mass			X
Shape - dimensions			X
Module location			X
Effector interface			X
Alignment during removal/replacement	X		
Markings			
Identification markings			X
Alignment aids			X
Beacon lights			
Brightness			X
Number			X

MANIPULATOR SYSTEM EVALUATION CRITERIA

Category: II. Subsystem Criteria - Worksite Interface

Criteria	Perform Parameter	Engineering Parameter	System Parameter
	Levels of Criteria		
Location			X
Repetitum rate			X
Duty cycle			X
Ranging beacons - location			X
Response			X
Dynamic effects			X

MANIPULATOR SYSTEM EVALUATION CRITERIA

Category: II. Subsystem Criteria - Mobility System - FFTS

Criteria	Levels of Criteria: Perform Parameter	Engineering Parameter	System Parameter
Body axis rotation			
Angles of rotation		X	X
Rates		X	X
Accelerations		X	X
Dead band		X	X
Body axis alignment			
Accuracy of linear alignment	X		
Accuracy of rate matching	X		
Propellant expenditures			
ΔV	X		
Rotational propellant	X		
Translational propellant	X		
Rotation control			
Accuracy	X		
Handling qualities	X		
Proportionality of control	X		
Time delays	X		
Alternate modes			X
Translation control			
Accuracy	X		
Proportionality	X		
Time delays	X		
Alternate modes			X

MANIPULATOR SYSTEM EVALUATION CRITERIA

Category: II. Subsystem Criteria - Mobility System - FFTS

Criteria	Levels of Criteria: Perform Parameter	Engineering Parameter	System Parameter
Power requirements		X	
Stowed volume		X	
Deployed volume		X	
Weight		X	
Mass handling capability	X		
Force application capability	X		
Operation duration capability	X		
Backup system availability			X

MANIPULATOR SYSTEM EVALUATION CRITERIA

Category: II. Subsystem Criteria - Man-Machine Interface

Criteria	Levels of Criteria: Perform Parameter	Engineering Parameter	System Parameter
Workstation arrangement			X
Reach envelope			X
Visual envelope			X
Panel configuration			X
Panel lighting			X
Station ingress/egress time	X		
Emergency egress provisions			X
Control - display integration			X
Control system interface			
Capability of long duration hold	X		
Control cross coupling - cross talk	X		
Operating envelope			X
Alternate modes			X
Interference with other control	X		
Time to initiate control input	X		
Control accuracy - precision	X		
Probability of inadvertent activation	X		
Probability of substitution error	X		
Probability of adjustment error	X		
Time to perform	X		
Relationship to other controls	X		
Display system interface			
Number of active displays			X

MANIPULATOR SYSTEM EVALUATION CRITERIA

Category: II. Subsystem Criteria - Man-Machine Interface

Criteria	Levels of Criteria		
	Perform Parameter	Engineering Parameter	System Parameter
Degree of display sharing			X
Probability of reading error	X		
Probability of substitution error	X		
Accuracy of spatial orientation	X		
Accuracy of eye-hand coordination	X		
Operator visual capabilities			
Acuity	X		
Motion resolution	X		
Depth judgment	X		
Form discrimination	X		
Brightness discrimination	X		
Pattern recognition	X		
Size estimation	X		
Alignment	X		
Motion discrimination	X		
Operator non-visual capabilities			
Force discrimination	X		
Shape discrimination	X		
Contact sensing	X		
Operator Workload			
Degree of loading	X		X
Physical load	X		X
Mental load	X		X

MANIPULATOR SYSTEM EVALUATION CRITERIA

Category: II. Subsystem Criteria - Man-Machine Interface

Criteria	Levels of Criteria: Perform Parameter	Engineering Parameter	System Parameter
Operator characteristics			
Number			X
Allocation of functions among operators			X
Allocation of functions - man and machine			X
Decision aids			X
Skills and skill levels			X
Duty cycles			X

MANIPULATOR SYSTEM EVALUATION CRITERIA

Category: II. Subsystem Criteria - Visual System

Criteria	Levels of Criteria: Perform Parameter	Engineering Parameter	System Parameter
Visual system characteristics			X
Field of view			X
Resolution			X
Registration			X
Contrast			X
Frame rate			X
Look angle - aspect			X
Camera - manipulator interface			X
Transmission characteristics			
Signal/noise ratio			X
Levels of signal ditization			X
Bandwidth			X
Display Criteria			
Reference system - coordinates			X
Monitor size			X
Monitor location			X
Depth of view			X
Display location W.R.T. operator			X
Software requirements			X
Number of displays - views			X
Color - brightness contrast			X
Control of display			
Azimuth sweep - pan			X

MANIPULATOR SYSTEM EVALUATION CRITERIA

Category: II. Subsystem Criteria - Visual System

Criteria	Levels of Criteria: Perform Parameter	Engineering Parameter	System Parameter
Elevation sweep - tilt			X
Magnification - zoom			X
Display sharing			X
Display selection			X
Lighting			
Range of intensities			X
Control of illumination			X
Angle of illumination			X
Spectral response			X
Display aids - availability & adequacy			
Vehicle alignment	X		
Manipulator alignment	X		
Navigation	X		
Position control	X		
Rate control	X		
Component identification	X		
Inspection	X		
Aid parameters			
Scaling			X
Type			X
Duration of display			X
Line resolution			X
Symbology			X
Software Requirements			X

MANIPULATOR SYSTEM EVALUATION CRITERIA

Category: II. Subsystem Criteria - Manipulator Control/ Controller

Criteria	Levels of Criteria: Perform Parameter	Engineering Parameter	System Parameter
Position indexing - repeatability	X		
Rate indexing - repeatability	X		
Force indexing - repeatability	X		
Time to initiate control sequence	X		
Number of df simultaneously controllable			X
Position accuracy - tip placement	X		
Orientation accuracy - effector and arm	X		
Control linearity		X	X
Control sensitivity		X	X
Control cross coupling		X	X
Control proportionality		X	X
Control mode - position, rate, both			X
Minimum bit input - position			X
Minimum bit input - rate			X
Feedback sensor integration			X
Applicability to time delay conditions		X	
Control logic - software requirements		X	
Dual arm control capability		X	
Degree of control integration		X	
Feedback at controller			
Position and rate			X
Effector orientation			X
Forces/torques/contrasts			X

MANIPULATOR SYSTEM EVALUATION CRITERIA

Category: II. Subsystem Criteria - Manip. Control/Controller

Criteria	Levels of Criteria		
	Perform Parameter	Engineering Parameter	System Parameter
Controller safety		X	
Controller reliability/maintainability		X	
Controller sharing		X	
Anomalie detection accuracy	X		
Obstacle detection time	X		

APPENDIX B

TEST PLANS FOR MANIPULATOR SYSTEM EVALUATION STANDARDIZED TESTS

MANIPULATOR SYSTEM EVALUATION TEST PLAN
EXPERIMENT 1 - TKA TASK EVALUATION

Objectives

The objective of this test is to gather time and accuracy measures for wire cutting and wire stripping tasks using a master-slave, semi-exo-skeletal anthropomorphic remote manipulator system equipped with TKA (terminal kit assembly) effectors. Measures will be gathered in a television feedback viewing condition for later comparison with similar tests given under conditions using a suited/gloved astronaut at the task site.

Methods and Procedures

Prior to testing, the experimenter will check all video and manipulator control systems. The task site will be prepared by the experimenter. TKA tools will be laid out in their storage mode. Task material will be stored to the side of the task site. Instructions will be read to the subject explaining exactly what the task involves. The subject will then be fitted to the ADAMS Control Master and allowed five minutes of exercising both arms as a warm-up procedure. Each subject will have already received hands-on training and other instruction in the operation of the ADAMS manipulator. At the end of the five minute warm-up period the experimenter will instruct the subject to rest the manipulators at the assigned "task start" position. The left manipulator (L) shall be fitted with an ADAMS II end effector. From the "task start" position the subject will command the right manipulator to the TKA storage area and extract the diagonal pliers/wire cutters from the storage bay. The subject shall then command the left manipulator arm to a position at the wire storage area and command extraction of the first wire. Each wire will be 10 cm long. Ten wires each of 10, 14, & 18 gauge shielded wire shall be used by each subject in this experiment. A high contrast marking 1 cm wide on each wire will be used as the cutting target. L will present the wire in an orientation such that it can be cut by the TKA wire cutter affixed on R. The cut shall be made over a scrap wire box into which the cut end can fall. The cut will be made at the distal end of the cut target marking. The subject shall then command R to the TKA storage bay and store the wire cutter. Next, R extracts the wire stripper from storage. L then orients the section of wire so that R can strip the wire. The wire stripper should be applied to the wire section and operated so as to remove the remaining portion of the 1 cm target marking. L will then be commanded to store the finished wire and R to store the wire stripper in TKA storage. The subject will then return both arms to the rest position before proceeding to the next trial.

Experimental Design - Test 1

General

Manipulator System

- Advanced Anthropomorphic Manipulator System (ADAMS)

End Effectors

- Left Effector - ADAMS II
- Right Effector - TKA
  - diagonal pliers/wire stripper

Viewing System

- Television Viewing
- Cohu Camera System
- Conrac Monitor System

Subjects

- Right Hand Dominant
- Normal Vision/Corrected Vision

Independent Variables

3 wire sizes - presented in random order

- 10 gauge
- 14 gauge
- 18 gauge

Dependent Variables

- Whole Task Time
- Subtask Times
- Accuracy of Cut
- Accuracy of Strip

Control Variables

- Subject in a Standing Position
- Ambient Lighting at Task
- Type and Length of Wire
- Position and Width of Target Cut Marking

Expected Results

It is expected that this experiment will yield human operator performance data which can be used to develop a data base for human controlled manipulator tasks using televised feedback. These data can then be compared with results of tests carried out under non-manipulator (suited astronaut) conditions.

MANIPULATOR SYSTEM EVALUATION TEST PLAN
EXPERIMENT 2 - MINIMUM POSITIONAL CHANGE

Objective

The objective of this experiment is to determine the human operator performance and controller-manipulator capabilities in making small changes in effector tip position.

Apparatus

A task module .31 m square with instrumented targets mounted as indicated in Figure B-1.

Each target will be instrumented so as to generate a signal when contracted by a wire stylus fitted to the effector.

The task module will be mounted to a task board which can be moved to any of 3 distances from manipulator. The manipulator will be fitted with a one inch spring loaded metal stylus to close the signal generation loop upon target contact.

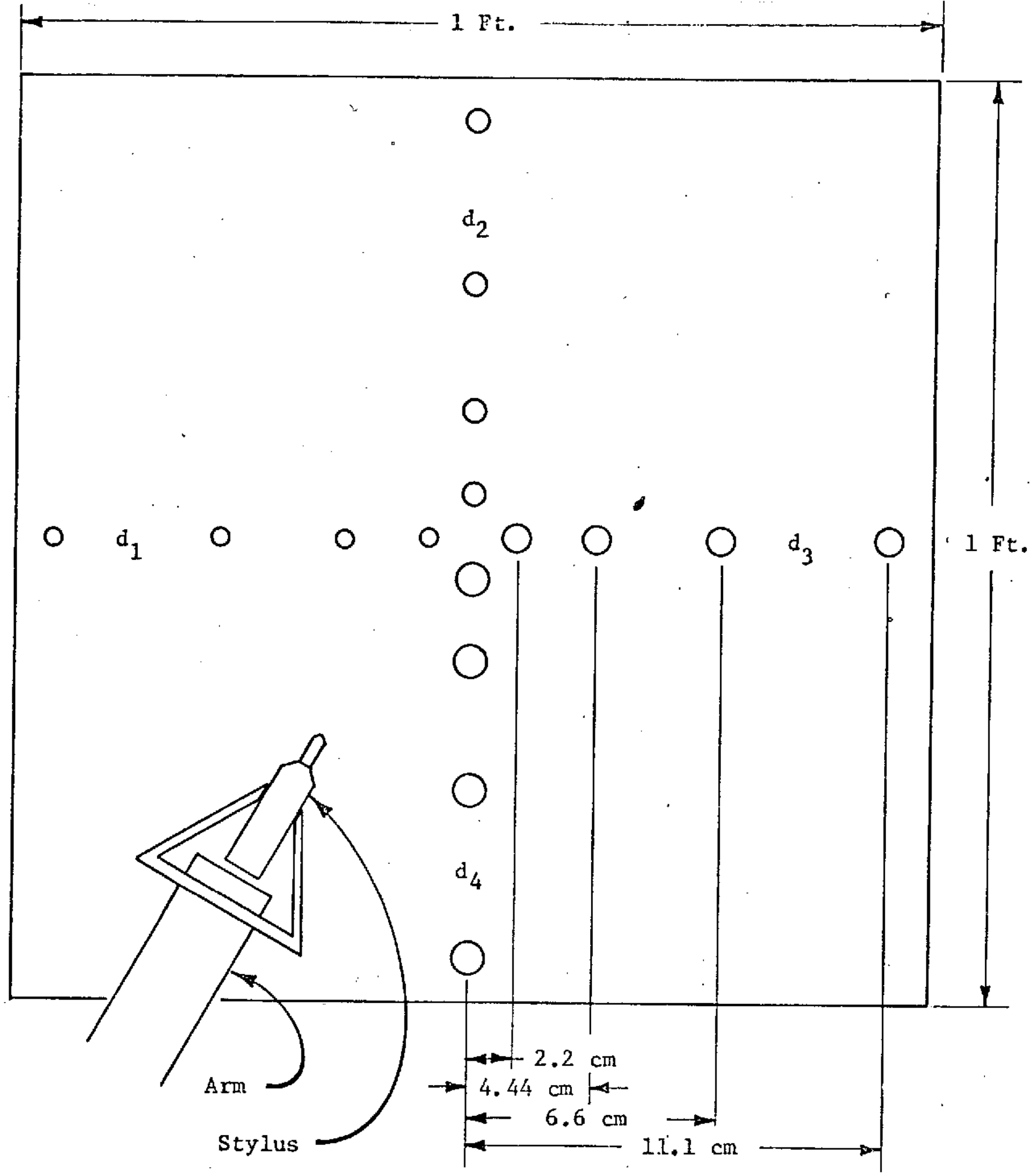
Experimental Design

The independent variables will include:

4 controller-manipulator configurations
1) TBD-AMES
2) ADAMS-ADAMS
3) ESAM-ESAM
4) TBD-RAM

4 target sizes
1) .7 cm
2) 1.0 cm
3) 1.3 cm
4) 1.6 cm

4 target separations from the central position of 0
1) 2.2 cm from 0
2) 4.4 cm from 0
3) 6.6 cm from 0
4) 11.1 cm from 0



(Not Drawn to Scale)

Target			Diameter
1= O	2 x s	d_1	.7 cm
2= O	3 x s	d_2	1.0 cm
3= O	4 x s	d_3	1.3 cm
4= O	5 x s	d_4	1.6 cm

. Record time from loss of contact with middle position to contact with target

FIGURE B-1. Task Module for Minimum Position Change Test

2 orientations of targets with respect to the manipulator axes
1) Horizontal
2) Vertical

Manipulator reach envelopes
1) Maximum
2) 1/2 of Max. & Min. (Midpoint)
3) Minimum

The control variables will be set at the following levels:

TV image geometry
1) Fixed camera - normal to task
2) Mobile camera

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

Ambient lighting at task board
1) 100 foot candles

The dependent variables to measured are:

Time for commanded positional change

Accuracy of commanded positional change

Procedure

The subject will receive instructions from the experimenter and then proceed with the training trials. After the training trials the experimenter will repeat instructions.

The experimental trials shall begin with the subject viewing the arrangement of targets on the task module through the TV monitor. The sequence will begin with the subject moving the end effector from a reference position and contacting the central target with the stylus. The signal denoting contact will be sent to a magnetic tape recorder. The experimenter will observe procedure through a repeat of subject's video. After initial contact the experimenter will verbally command the subject to move the effector to another target. The targets will be 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 has made contact with the commander's target an impulse will be sent to the magnetic tape recorder and also terminate a digital clock in the experimenter's station. The digital clock will be active from the time contact with target 0 is broken until contact is made with commander's target. After contact, the experimenter will verbally command the subject to return stylus to target 0 and then proceed to next trial. 16 trials will be run for each of 4 quadrants for a total of 64 trials. In each quadrant there will be 4 trials for each of the 4 separations. Each block of 64 trials will be run for maximum, midpoint, and minimum manipulator reach which is 192 trials for each of 5 subjects. All trials at one reach condition will be run before proceeding to the next condition. All trials for one controller-manipulator configuration will be run before going to the next configuration. This will result in 192 trials per 5 subjects per 4 configurations or 3840 trials for the test. If each trial requires 30 seconds, this results in 34 hours of testing time. This does not include time for setup, calibration or system change over.

Discussion

It is expected that this experiment will provide information regarding human operator performance and alternate controller-manipulator configuration capabilities in tasks requiring small, discrete positional adjustments of the manipulator tip.

Data will be gathered on task time (movement from 0 to command target) and task accuracy (the ability of the system to perform the positional change).

Descriptive and inferential statistics will be computed to describe and compare the alternate system capabilities.

MANIPULATOR SYSTEM EVALUATION TEST PLAN
EXPERIMENT 3 - CARGO MODULE REMOVAL/REPLACEMENT

Objective

The objective of this test will be to determine the human operator performance and alternate controller-manipulator configuration capabilities to perform module removal/replacement and cargo transfer.

Apparatus

Three cargo modules (CM) varying in volume. The 1st CM will be 1 x 1 x 1 foot cube, the second will be a 3 x 12 x 24 inch "panel", the third will be a "tray" 9 x 9 x 16 inches. The first CM will be 1.0 cubic feet, the second will be 0.5 cubic feet and the third, 0.75 cubic feet.

Three task modules, each one foot square will be used to accept the CM's. The task modules will be instrumented to record number and place of CM contact with the retaining receptacle during insertion and extraction of the CM's from the task module.

The CM receptacle will be outfitted with a multi-pin plug at the back to record contact and lock as the CM is inserted or extracted. The receiving edges of the receptacle will be such that the clearance allowed for the CM can be varied from 1/16 to 1/4 inches on each side.

A zero g simulation device will be attached to the CM's -- a balloon or suspension rig -- to simulate satellite cargo transfer.

A CM storage area will be required off to one side of the task board.

Experimental Design

The independent variables will include the following:

4 controller-manipulator combinations - standard

3 module sizes
1) 1 cu. ft. cube 12 x 12 x 12
2) .50 cu. ft. "panel" 3 x 12 x 24
   a) horizontal
   b) vertical
3) .75 cu. ft. "tray" 6 x 6 x 36

2 types of module handles
1) "gloved astronaut" handle
2) "manipulator specific" handle

2 task module clearances
1) 1/16 inch
2) 1/4 inch

The control variables will be set for the following subsystems:

1) Lighting - standard - 100 fc at task board
2) Video parameters - standard - analog 4.5 MHz, 32 db S/N
3) Manipulator gains - standard
4) Subject procedures - standard

The dependent variables to be measured are:

1) Forces and torque exerted
2) Time to perform tasks

Procedure

The subject will receive instructions from the experimenter and proceed with the selected number of training trials. The experimenter will then repeat the instructions and proceed to experimental trials.

The subject will view a CM in position in the task module. He will then move the manipulator from a reference position, grasp the CM, apply a pulling force to remove the CM and move it to a storage location to the right of the task board. He will then move the manipulator to the left side of the task board and pick up an equivalent CM, move the replacement to the receptacle and insert it. The manipulator will then be returned to the reference position before proceeding to the next extract insert task. Five trials with the same CM at the same orientation will be run before the assistant changes the task.

Contact at the back of the receptacle will be sensed and recorded. Time to complete each 5-trial sequence as well as each individual operation will be recorded.

Discussion

It is expected that this experiment will yield information on manipulator system capabilities in module removal, transfer and replacement similar to requirements involved in satellite servicing missions.

Contacts and time data will be subjected to descriptive and inferential statistical analysis. This will indicate relative performance measures for each alternate configuration.

There are three CM's and two orientations for the "panel" which yield four variables. Two types of CM handles will be investigated, and the task modules will be manipulated with two clearances. This yields 4 x 2 x 2 or 16 levels. There will be five replications performed on four systems by five subjects which yields 5 x 4 x 5, 100 x 16 or 1600 trials. If each trial takes three minutes, the total test time will be 80 hours. This does not include checkout, calibration or setup time.

MANIPULATOR SYSTEM EVALUATION TEST PLAN
EXPERIMENT 4 - TIP POSITION ACCURACY

Objective

To determine human operator performance in achieving and holding a designated manipulator tip position for 15 seconds.

Apparatus

A task module equipped with a .31 m square metal plate, with 6 concentric circles. The inner circle will be twice the stylus diameter in size, and each succeeding circle will increase in diameter by that same size factor.

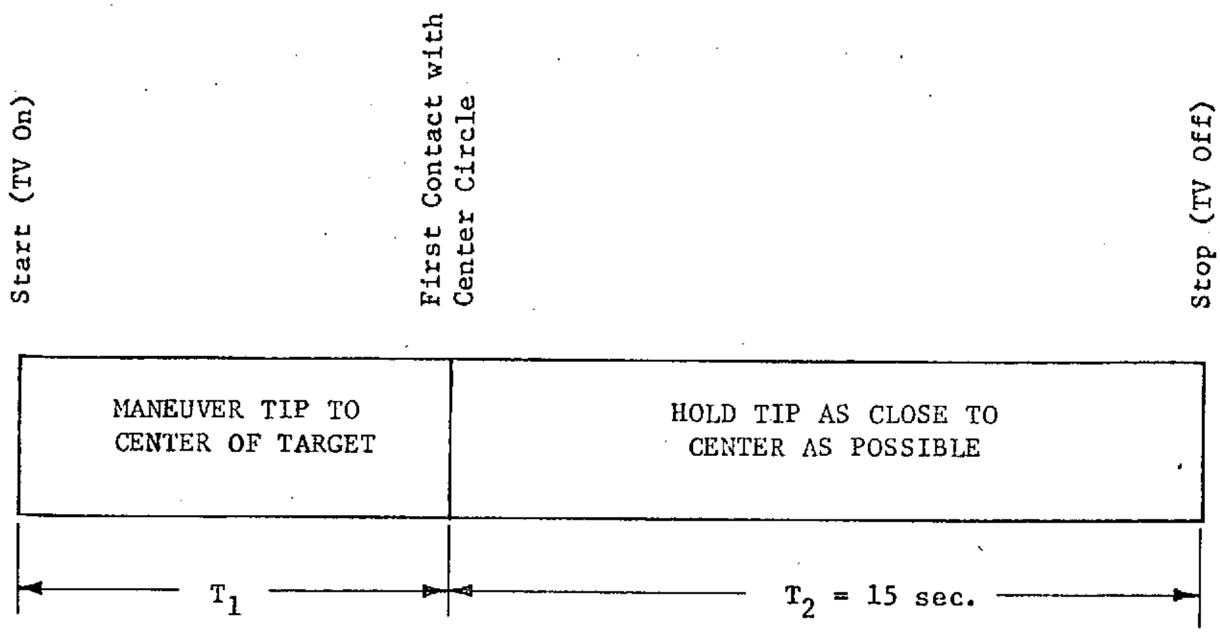
The task module will be mounted on an adjustable-movable stand to enable positioning of the plate at anu location within the reach envelope of the manipulator as shown in Figure B-2. The plate will be adjustable in two rotational degrees of freedom so that the plate, at any location, can be positioned in a plane normal to the TV camera line-of-sight.

A spring loaded wire stylus one inch long, and of a contact diameter .250 inch, will be fitted to the end effector which will close a circuit on contact with any one of the 6 concentric circles. When contact is made, a light will burn at the experimenter's station indicating with which ring contact has been made. A digital clock will be activated to measure the 15 second hold period.

Experimental Design

The independent variables will include:

4 controller-manipulator combinations
1) ESAM-ESAM
2) ADAMS-ADAMS
3) TBD-RAM
4) TBD-AMES



$$T_2 = \sum_{i=1}^{6} t_i$$

DEPENDENT MEASURES

$x(t)$ = Distance from Center to Stylus

t_i = Time in i^{th} ring $\quad i = \{1\text{---}6\}$

$$E_i = \frac{(2_i - 1)\ a}{2}$$

$$\text{Mean Error} = \sum_{i=1}^{6} E_i \frac{t_i}{T_2}$$

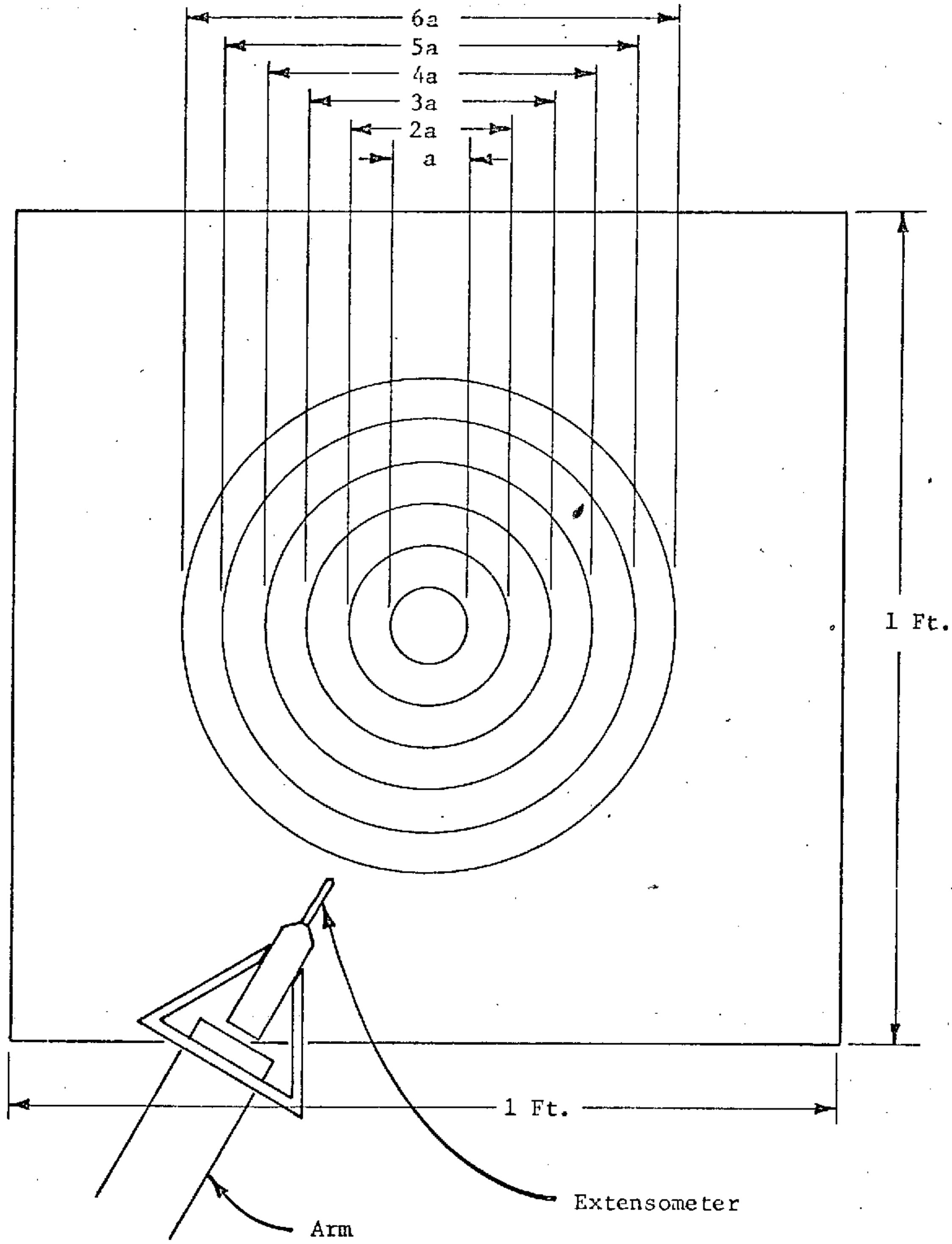
$$\text{SS Error} = \sum_{i=1}^{6} E_i^2 \frac{t_i}{T_2}$$

$$\text{Variance} = \text{SS Error} - (\text{Mean Error})^2$$

Range of Errors $<6a$ - Adjust a

$$\sqrt{\text{Variance}} \approx a$$

FIGURE B-2. Tip Position Accuracy



(Not Drawn to Scale)

- One Foot Square Board Mounts in 5 Positions on Task Board (Standard Module Base)
- Concentric Rings - Conducting Material with Min. Thickness Insulation Between
- Arm Holds a Stylus Which Can Complete a Circuit Through any of the Rings
- Data - Time from TV Onset to First Contact W. Center Circle Contact Time for Each Ring
- Timing of 15 Sec. Hold Period is Required

FIGURE B-2, Continued

5 designated positions of the task board varying in 5 dimensions. Each position will be presented twice.

The control variables will include the following:

1) Ambient lighting
2) Video parameters
3) Manipulator gains
4) Subject procedures

The dependent variables to be measured are:

1) Accuracy of initial positioning
2) Time to initially position
3) Accuracy of position hold over 15 seconds

Procedure

The subject will get task instructions from the experimenter. The subject will then proceed with training trials on the task. Following the training trials the experimenter will repeat instructions to the subject prior to experimental trials. The subject will be given a video image of the task module containing the 6 concentric circles. At the onset of the video image, the subject will move the manipulator with attached stylus from a fixed reference position to the target on the task board. The task will be to place the stylus as close to the center of the target as possible. When contact between stylus and target is made, a light and timer will be activated--the timer being used by the experimenter to check the 15 second position hold and the light indicating contact for both the subject and the experimenter. At the end of the 15 second hold, the experimenter will command the subject to return the manipulator to the reference position. The video at the subject's station will be terminated while the experimenter's assistant changes the position of the task board. The experimenter will then initiate the next trial.

The time and position accuracy data will be collected at the experimenter's station using appropriate collection devices. The experimenter will monitor the test site through a repeat of the subject's TV monitor, and the experimenter will monitor the subject through a camera located in the subject's station.

Discussion

It is anticipated that this experiment will produce appropriate measures of operator-controller-manipulator accuracy in tip positioning tasks. Relative effectiveness of alternate systems will be analyzed.

Descriptive and inferential statistics will be computed to describe the performance of each controller-manipulator combination, and to compare the performance of these combinations.

A total of 25 positions will each be tested twice for each of 5 subjects. This results in 250 trials for each controller-manipulator combination. Since 4 combinations are to be tested, there will be 1000 trials in this experiment.

All trials, for all subjects will be run on one controller-manipulator combination before testing begins on the next combination.

If each trial and setup takes 90 seconds a total of 25 hours will be needed to run all trials. This does not include system checkout and calibration times, nor does it include analysis.

MANIPULATOR SYSTEM EVALUATION TEST PLAN
EXPERIMENT 5 - TIP POSITION ORIENTATION

Objective

To determine operator/manipulator system ability to acquire and hold a designated tip orientation with respect to a work surface.

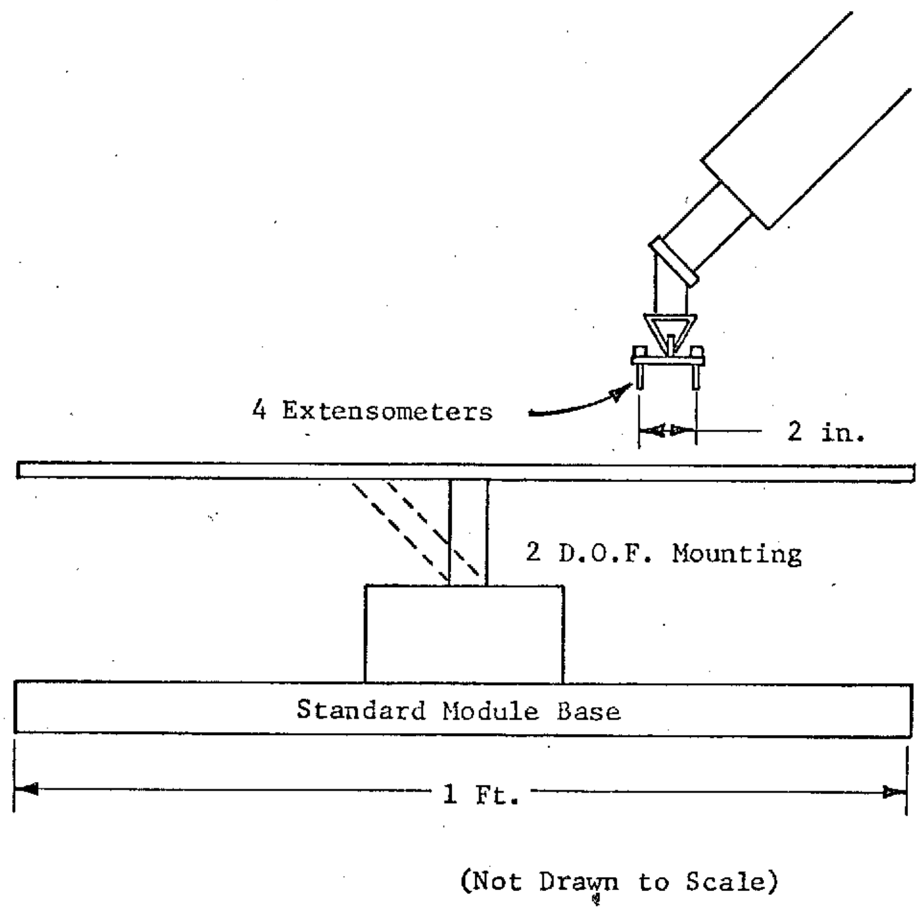
Apparatus

A basic module with a conductive plate mounted on it via a two degree hinge mount. The conductive plate should be capable of $\pm 10^{\circ}$ $\pm 30^{\circ}$ with respect to the module board in either of two D.O.F. A two inch square non-conductive plate with a handle for the manipulator to grasp will also be required as indicated in Figure B-3. This plate will have 3 separate contacts. Each contact will complete a circuit when it touches the conductive plate. An on-off voltage signal will be recorded on a separate magnetic tape channel for each contact. In addition, the contact circuits will control relays in series so that a timer runs when all 3 sensors are in contact with the conductive plate. A separate timer will be required to implement the 15 second hold period. The 15 second period begins when all 3 sensors first make contact. Finally, a timer will be required to measure the time from TV onset until all three sensors make contact.

Experimental Design

The independent variables will include:

2 levels of effector orientation
1) Tip normal to workplace plane
2) Tip parallel to workplace plane



- Analog Tape Recording (4 Channel) for Each Contact Sensor
- Time to First Contact of All 4 Sensors
- Max Angle 30° or Greater
- Timer for 15 Sec. Hold Period
- Contact Plate Rigidly Held by End Effector

FIGURE B-3. Task Module for Tip Position Orientation Test

9 orientations of the module with respect to the main task board

1) Parallel
2) 10° yaw right
3) 30° yaw right
4) 10° yaw left
5) 30° yaw left
6) 10° pitch down
7) 30° pitch down
8) 10° pitch up
9) 30° pitch up

3 positions of the module on the task board

1) Center
2) Upper right
3) Lower left

2 levels of camera placement

1) Fixed
2) Mobile

4 controller-manipulator combinations

1) ADAMS-ADAMS
2) ESAM-ESAM
3) TBD-RAM
4) TBD-AMES

Procedure

The subject will be instructed to move the end effector to the workplace, orient the effector so that the 2 inch plate is parallel to and in contact with the conductive plate, and to hold the orientation for 15 seconds. A timer will start when the TV display is switched on and will stop when all three sensors contact the plate. This timer will measure the time to orient. A second timer will start when 3 point contact is made and will be used to terminate the 15 second hold period. During the hold period, the voltages from each sensor will be recorded on magnetic tape and a timer will run when all 3 contact circuits are closed.

All trials with one controller-manipulator combination will be completed before any other combination is tested. Each module position and TV camera placement will be blocked within controller-manipulator combinations. Effector orientation and workplace orientation will be randomized. Subjects will receive 2 practice trials under each combined level of controller-manipulator and TV camera position. One hundred twelve trials will be required to complete the experimental design under each controller-manipulator combination. Assuming 90 seconds per trial and 5 subjects, approximately 56 hours of testing will be required.

The dependent measures will include the time to orient the end effector, the per cent of the 15 second hold period during which all 3 sensors maintain contact and the per cent contact time for each sensor taken independently and in pairs. This will permit detection of biases in non-alignment direction. Differences in these measures due to controller-manipulator combinations and due to the other independent variables will be assessed via analysis of variance.

MANIPULATOR SYSTEM EVALUATION TEST PLAN
EXPERIMENT 6 - MANIPULATOR DEXTERITY

Objective

To determine operator/manipulator performance in carrying out fine positioning of objects of varying size.

Apparatus

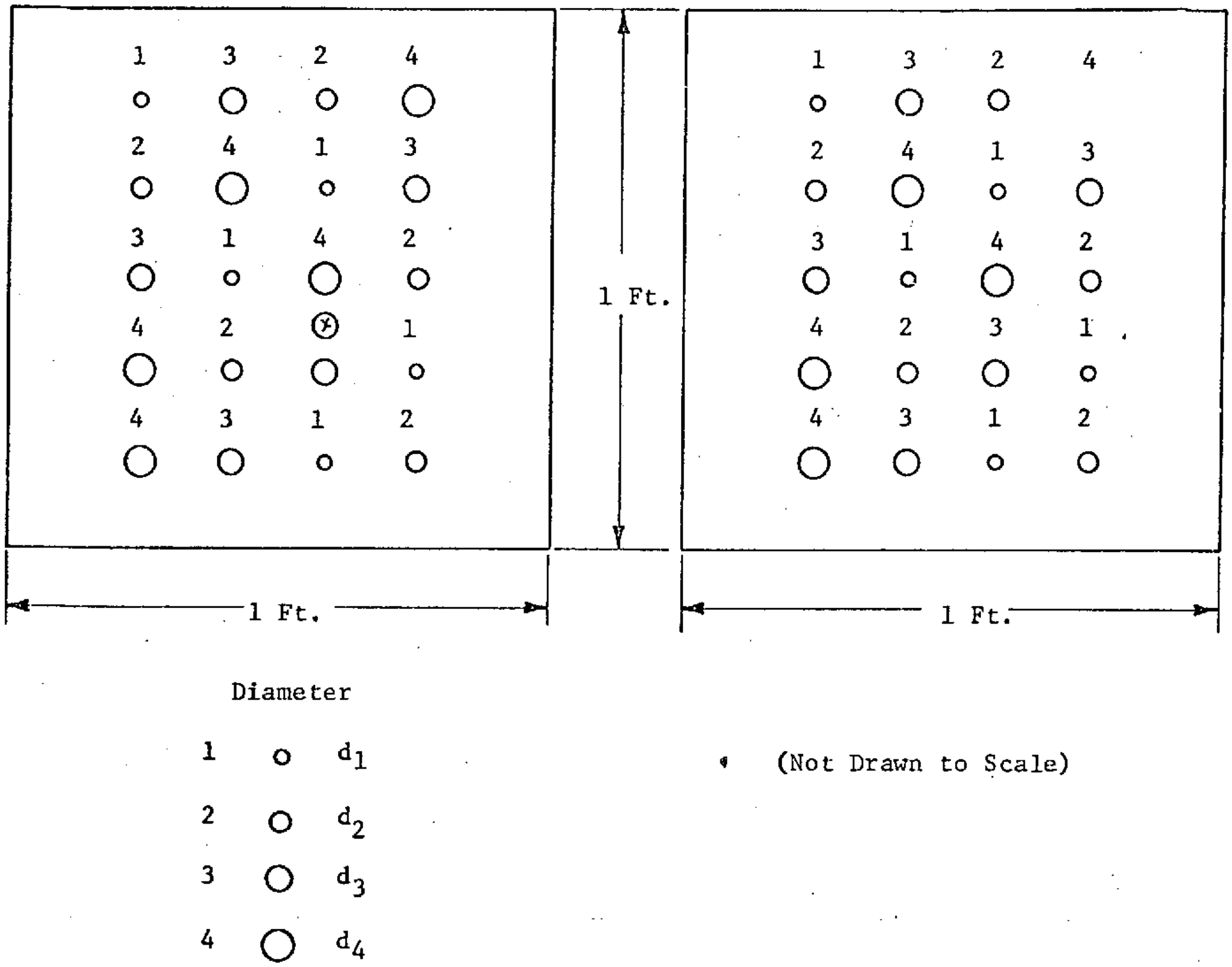
Two standard modules each containing a 4 x 5 matrix of holes. The holes will be of four different diameters and the various diameters will be located at random on the module as shown in Figure B-4. The same random pattern will be used on both boards. The holes will contain conical pegs of the appropriate size. Each hole will contain a switch. A contact circuit will be set up for each of the 20 hole pairs composed of the corresponding holes of modules A and B. The circuit should be designed so that a timer starts when the peg leaves a hole in Board A and stops when the peg is placed in the appropriate Board B hole. Possibly one timer could be used with decade switches to select the proper contact circuit.

The modules A and B should be interchangeable in position so that both left-to-right and right-to-left movements may be made. Provision will be required for mounting the entire task board in either a vertical or horizontal position.

Experimental Design

The independent variables will include:

4 levels of Peg/Hole size
T.B.D.



- 5 Pegs/Holes per Size
- Microswitch or contact in each hole
- Time from removal to placement for each peg from the Removal Module to the Placement Module
- Switch Logic differs between removal and placement modules
- Could use one clock and decade switches between the 20 peg circuits

FIGURE B-4. Task Module for Manipulator Dexterity Test

2 levels of task board orientation
1. vertical
2. horizontal

2 directions of movement
1. right-left
2. left-right

4 controller-manipulator combinations
1. ADAMS - ADAMS
2. ESAM - ESAM
3. RAM
4. AMES

Procedure

The subject will be instructed to grasp a particular peg in Board A, remove it, and place it in the corresponding hole in Board B. The appropriate peg circuit will be switched in and the time to complete the movement will be recorded. The experimenter will note any peg selection - replacement errors - although these reflect perception and decision making more than manipulator control.

All trials with one controller-manipulator combination will be completed before any other combination is tested. Within controller-manipulator combinations, module position (direction of movement), and camera position/FOV will be blocked. The remaining variables will be randomized. Each cell of the design matrix will be replicated 3 times. There are 32 trials per subject per controller-manipulator combination required by the design matrix. With replications, 96 trials are required. Subjects will receive 2 practice trials under each combination of controller-manipulator, camera position FOV, and task manipulator condition. Assuming 5 subjects and 30 seconds per trial, a total of approximately 19 hours for the entire test.

Dependent measures will include peg positioning time and error frequency. These data will be subjected to analysis of variance to assess differences between controller-manipulator combinations and between levels of the remaining variables.

MANIPULATOR SYSTEM EVALUATION TEST PLAN
EXPERIMENT 7 - FASTENER CONNECT/DISCONNECT

The objective of this experiment was to determine human operator performance and alternate manipulator configuration capabilities in operating a range of five fasteners.

Task Specific Apparatus

A task module which will accept for mounting each of five fasteners. Instrumentation to denote fasten/disconnect will be integrators in the task module.

Experimental Design

The independent variables will include the following:

A controller/manipulator configuration's standard

5 fasteners
- Task - A quarter turn lock/unlock fastener
- Task - A push-in lock/unlock fastener
- Task - A "carpenter box" latch fastener
- Task - A quarter turn "dog" latch
- Task - A multi turn wheel for hatches

The control variables will be set at the following levels:

Lighting - 100 F.C.
Video parameters - Analog 4.5 MHz, 32 db S/N
Manipulator gains - Standard
Subject procedures - Standardizors

The dependent variables to be measured are:

Time to complete a fastening/unfastening

Methodology

The experimenter (E) will read the instructions to the subject (S) who will then perform five training trials. E will repeat the instructions to

S prior to experimental trials. S will view a task module with one of the five fasteners attached. On command S will move the manipulator to the task board and fasten and unfasten the fastener five times for each operation. A check will be made to validate fasten/unfasten status of fastener. When the ten operations are performed on one fastener, the laboratory assistant will change fasteners on the module and repeat for all five fasteners. Each block of trials will be repeated three times.

General Discussion

It is expected that this experiment will yield data on selected configurations of controller/manipulator systems and their capabilities in manipulating selected fasteners. Data will also be gathered on alternate fastener systems.

The data will be subjected to statistical analysis to compare systems performance, and to indicate individual system performance.

A total of ten fasten/unfasten operations will be made for each block with one fastener. Therefore, for five fasteners and three replications there will be 150 trials for each of five subjects for a total of 750 trials. If each trial takes 60 seconds to complete this would equal 12.5 hours of test time. This does not include the time necessary for test setup and calibration.

MANIPULATOR SYSTEM EVALUATION PROGRAM REQUIREMENTS
EXPERIMENT 8 - DISTANCE ESTIMATION

Objective

To determine the effects of video system parameters and manipulator movement on the human operator's capability to judge separation distances and complete separation tasks.

Apparatus

A task table 4x4 ft. which will be painted or covered with a non-reflective black surface. The task board will be divided into one inch squares so that the experimenter can accurately place target pegs anywhere on the task board.

A set of wooden pegs all one inch in diameter, but varying in height -- two pegs shall be three inches tall and the four others shall be 2.4 inches, 2.7 inches, 3.3. inches and 3.6 inches or vary - 20% - 10%, +10%, +20% of the height of the three inch pegs. All six of the hardwood pegs will be painted to a reflectivity of .7.

Experimental Design:

The independent variables will include:

2 controller-manipulator combinations
1. ESAM-ESAM
2. TED-AMES

2 directions of peg movement
1. fore
2. aft

15 positions of 2 pegs around a zero point center for both lateral and fore & aft separations

Fore Aft	x	Lateral
1. none		1. 1"
2. 1"		2. 4"

3. 3"
4. 7"
5. 12"

3. 10"

5 heights of one inch diameter pegs compared to a standard 3 x 1 in. cu. peg.

2.4, 2.7, 3.0, 3.3 and 3.6 inches

3 video system parameters

1. one camera mono, at 0°/0°
2. one camaera stereo, at 0°/0°
3. two orthogonal mono cameras, at 0°/0° & 90°/0°

The control variables will include the following:

1. Ambient Lighting - 100 F.C.
2. Peg reflectors - .7
3. Manipulator gains - Standard
4. Subject procedures - Standardizor

The dependent variables to be measured are:

1. Accuracy of distance estimation
2. Accuracy of eliminating the distance - fore/aft between the pegs using the manipulator to move the designated peg

Procedure Methodology:

The experimenter will place the standard 3-inch peg and one of the five comparison pegs at pre-determined positions on the task board. The subject will be presented with TV images of the pins arranged in varying orientations with respect to fore/aft and lateral displacement. The subject will be told only that the pins are 1 inch in diameter. The initial task will be for the subject to estimate which of the two pins is closest to him; next, how far the pins are separated one from the other in the fore-aft plane, and then to move the manipulator to the pin fartherest away or closest to him in a counter balanced order and move that pin forward or back to null out any perceived fore-aft separation while still maintaining the pre-positioned lateral separation. The presentation of different sized pegs will be randomized for all subjects. The use of different TV systems will be blocked for all subjects so that all trials under one system will be run prior to changing systems, but the order of presentation of different systems will be randomized among subjects. The subject will report verbally his estimation of which peg is closest and the peg's force/aft separation, to the experimenter. The experimenter will record the errors in his attempt to null out this separation with the manipulator.

Discussion:

It is expected that this experiment will yield measures of depth estimation which can be compared with existing experimental findings dealing with separation estimation. The primary difference in this data and existing data is that this will include a dynamic task in that the manipulator will be used to reach out to, grasp and reposition one peg. Not only will data be gathered on estimations, but errors in reaching, grasping and repositioning will be recorded by the experimenter.

Descriptive and inferential statistics will be computors to described experimental performance.

A total of 15 peg positions, five differing peg heights and two directions of peg movement will yield 60 levels of variation for the pegs. All 60 levels will be tested under each of three video system parameters and the two controller-manipulator systems, yielding 360 trials for each of five subjects. The resulting 1800 trials should take three minutes each for a total test time of 90 hours.

All trials for all subjects will run on one controller-manipulator combination before testing on the other combination.

MANIPULATOR SYSTEM EVALUATION TEST PLAN
EXPERIMENT 9 - FORCE-TORQUE APPLICATION

Objective:

To determine forces and torques applied in specified axes as the operator attempts to use selected controller-manipulator systems to position an object along one axis. Positioning will require a target or nominal force/torque. Force/torque in other axes or excessive force/torque along the task axis constitute error.

Apparatus:

A 6 in. lever mounted at the center of a standard module which may be mounted on the main task board. The lever mounting should permit 4 D.O.F. which may be angular or translational. The lever should be free to move right-left (Y or roll), fore-aft (X or pitch), Up-down (Z), and to rotate in yaw. The degrees of freedom will be spring damped so that a particular force will be required to move the lever to a specified position in one axis. Spring constants are T.B.D. to measure the displacements (and hence the forces) along various axes, potentiometers for the axes will be required.

A visual indicator of the lever position along the task axis will be required. This will take the form of markings on the lever and scales with pointers (to indicate the desired position) associated with the task module.

Provision will be made for moving the entire task board assembly to permit testing at different levels of manipulator reach.

Experimental Design:

The independent variables will include:

4 levels of task axis

1. Right - left
2. Fore - aft
3. Up - down
4. Yaw

4 levels of direction/extent

Within each axis there are 2 directions, 2 extents or magnitudes (T.B.D.0 will be selected for each axis in each axis-specific direction.

3 levels of reach extent for each manipulator

1. Minimum
2. 1/2 (Maximum & minimum)
3. Maximum

4 controller-manipulator combinations

1. ADAMS-ADAMS
2. ESAM-ESAM
3. TBD-RAM
4. TBD-AMES

Methodology:

The subject will be instructed to move the lever to a specified position along one axis (the task axis). At the beginning of a trial, the lever will be in a neutral position on all axes. The subject will attempt to make the required positioning movements, first grasping the lever with the arm. During the movement time period, time histories of all 4 potentiometers will be recorded on magnetic tape for off-line analysis. A trial will terminate when the lever is properly positioned and is being held by the manipulator.

All trials with one controller-manipulator combination will be run before any other controller-manipulator combination tests are begun. Within combinations, reach levels will be blocked to minimize time spent re-positioning the task board. Subjects will receive 4 practice trials - one on each task axis - before data are collected under each controller/manipulator/ reach extent combination. During data trials, task axis, direction, and extent will be randomized.

Sixty trials will be required per subject per controller-manipulator cond. to complete the experimental design - 48 data and 12 practice trials. Each cell in the design matrix will be run twice yielding 108 trials per subject per controller/manipulator condition. This requires 432 trials per subject. Assuming 90 seconds per trial and 5 subjects, approximately 54 hours are required for the entire test.

The dependent measures for the experiment will be derived from the force/ torque time histories. The peak force, mean force, and R.M.S. force will be obtained offline through computer processing of data tapes. Each of these measures for each D.O.F. for each trial will constitute the basic data matrix. Differences in these measures as functions of controller-manipulator combinations, reach extents, task axes, and directions will be assessed through analysis of variance. Coordination with comp. lab personnel will be required to insure that the data are compatible with existing hardware and software.

MANIPULATOR SYSTEM EVALUATION TEST PLAN
EXPERIMENT 10 - ANTENNA DEPLOY

Objective:

To determine human operator performance and the capability of selected controller-manipulator systems in antenna deployment operations.

Apparatus:

A task module outfitted with a variable orientation antenna which can be extended and retracted. Position locks will be provided for maintaining the antenna at 5 locations; straight out from the task module, tilted 45 degrees up or down, panned 45 degrees right or left.

Force and torque sensors located at the base of the antenna and wired to an appropriate outlet for connection to data gathering devices. Apparatus for force/torque sensing used in test 5, will be used here.

Coding on the antenna which will indicate the approach of 1/2 extension and the achievement of 1/2 extension.

Experimental Design:

The independent variables will include:

5 directions of antenna orientation

1. Straight out from task module
2. Tilted 45° up
3. Tilted 45° down
4. Tilted 45° right
5. Tilted 45° left

4 levels of operation

1. Fully extend
2. 1/2 extend
3. Fully retract
4. 1/2 retract

2 locations of test module

1. In the center of the task board
2. In the upper right hand corner of the task board

4 controller-manipulator combinations

1. ADAMS-ADAMS
2. ESAM-ESAM
3. TBD-RAM
4. TED-AMES

The control variables will be set at the following levels:

1. Lighting - 100 foot candles
2. Video parameters - Analog 4.5 MHz, 32 db S/N.
3. Manipulator gains - standard
4. Subject procedures - treatment - by-subjects

The dependent measures to be taken are:

1. Time to perform each task
2. Forces and torques recorded at antenna base

Procedure:

The subject will receive test instructions from the experimenter and then try to extend and retract the antenna with the manipulator-controller system in a series of training trials involving 2 trials at each of the 5 positions, and the center-of-board locations.

The subject will be presented with the extendable antenna in one location on the task board (center or upper right) and in one of the five orientations (up, down, straight, left or right). Upon command from E, S will move the manipulator from a fixed reference position and grasp the end of the antenna. S will pull or push the antenna out or in either to full or 1/2 extension and return the manipulator to the reference position. Time to task will be measured from the initiation of closure on the end effector to the initiation of release on the end effector. The antenna will then be reset for the next trial.

All trials for one module location on the task board will be run before proceeding to the next set of trials at the other location. All trials for one manipulator-controller system will be run before repeating the experiment with other manipulator-controller systems. The orientation of the antenna will be randomized for each block of trials at one location. The location of the module will be counter balanced among subjects.

The experimenter will view the extend-retract operations through a repeat of the S's video. Time and force/torque data will be recorded on magnetic tape. The experimental assistant will change orientation and extend/retract of antenna prior to each trial.

Discussion:

It is expected that this experiment will reveal the capabilities and problem areas of alternate controller-manipulator systems in operations involving antenna deployment.

Descriptive and inferential statistical analyses will be performed to test performance capabilities of each controller/manipulator system. There are 5 antenna orientations, 2 module locations, and 4 operations. Each of the four operations will be repeated 3 times at each orientation for 60 trials. These 60 trials will then be performed at two locations for a total of 120 trials for each of 4 controller/manipulator systems. Each trial should take approximately 90 second, with each test taking 3 hours.

The total experimental time for 5 subjects and 4 combinations of controller/manipulator would therefore be 60 hours. This does not include setup and calibration time.