Donald R. Scott EB24

MCR 86-542
Contract NAS8-35184

Final
Report

May 1986

Teleoperator Human Factors Study

(NASA-CR-178930) TELEOPERATOR HUMAN FACTORS STUDY Final Report (Martin Marietta Aerospace) 68 p CSCL 05H

N88-24162

Unclas
G3/54 0146405

Date of general release 1 May 1988

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TELEOPERATOR HUMAN FACTORS STUDY

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FOREWORD

This document is submitted in accordance with the data requirements list of Contract NAS8-35184, Teleoperator Human Factors Study. It covers the work performed on Tasks 1 through 6 for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. It was prepared by Martin Marietta Denver Aerospace in response to Attachment A Paragraph E of the contract statement of work.

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ACRONYMS AND ABBREVIATIONS

A	Adequate
Alt	Alternatives
Anal	Analysis
Atch	Attachments
Auto	Autonomous
BW	Bandwidth
C/D	Controls/Displays
CAE	Canadian Aerospace Electronics
Cap	Capability
Cat	Category
Char	Characterization
Comp	Components
Compat	Compatibility
Cont	Control
DAT	Differential Aptitude Test
DOF	Degrees of Freedom
Def	Definition
Dev	Development
E	Early (time frame)
g	gravity
H/W	Hardware
HFRP	Human Factors Research Plan
I	Insufficient
I/A	Adequacy Suspected
I/F	Interface
Illum	Illumination
Info	Information
JPL	Jet Propulsion Laboratory
L	Late (time frame)
LaRC	Langley Research Center
M	Medium (time frame)
MITL	Man-in-the-Loop
MSFC	Marshall Space Flight Center
Manip	Manipulation
Mech	Mechanical
Mod	Module
Mtl	Material
NASA	National Aeronautics and Space Administration
No.	Number
Non-Op	Nonoperative
Op(s)	Operator(s), Operation(s)
PFMA	Proto-Flight Manipulator Assembly
Percep	Perceptual
Perf	Performance
Pos	Position
Proc	Processing
Qual	Qualification
R/T	Real Time
Rqmts	Requirements
S/C	Spacecraft

S/W	Software
Svc	Servicing, Servicer
Sys	System
Tech	Technology
Tele, Teleop	Teleoperation
Tol	Tolerant
V	Void
Xfer	Transfer

CONTENTS

CONTENTS

Figure

Table

INTRODUCTION

The Teleoperator Human Factors Study (THFS) effort includes the six major planned tasks listed below and shown in Figure 1:

1) Define a set of reference teleoperator tasks;

2) Define and describe technology and development issues, options, and alternatives;

3) Survey/assess previous studies;

4) Define missing elements of data/knowledge;

5) Define and characterize tests and experiments required to satisfy missing elements in a Teleoperator Human Factors Research Plan.

6) Define and document the implementation of the Teleoperator Human Factors Research Plan.

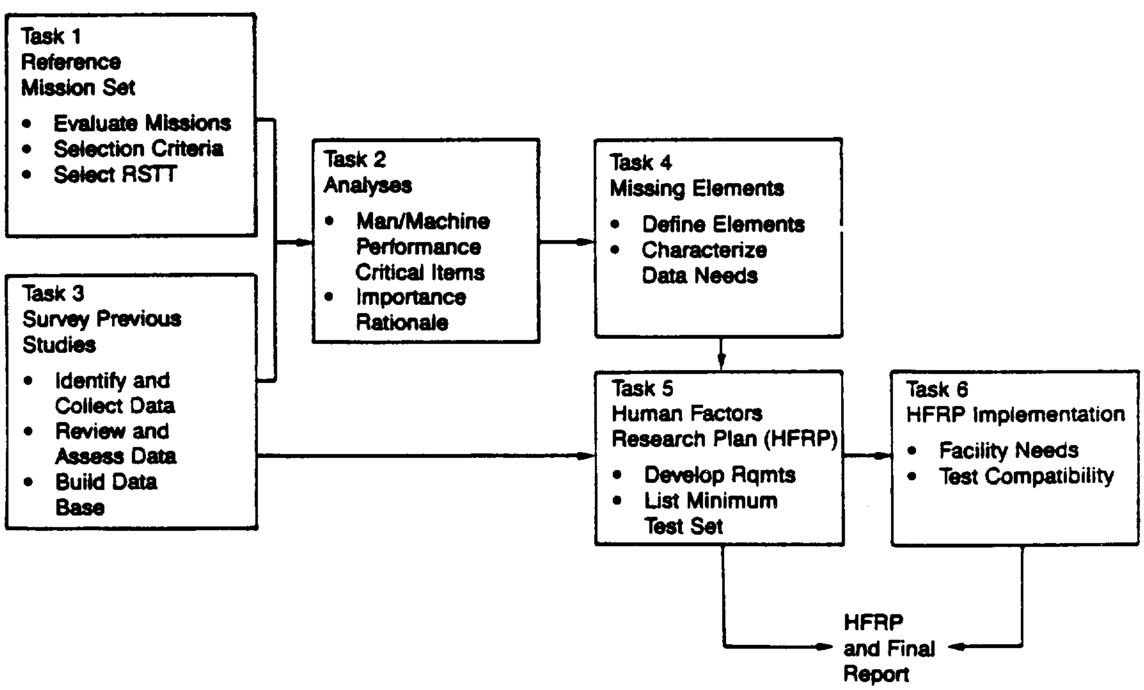

Figure 1 Study Flow

In the broadest terms, this study seeks to generate definitions, requirements, and supporting rationale for a series of tests, experiments, and/or analyses intended to (1) resolve critical human engineering issues and (2) characterize the effects of various design development options on the performance of a remotely located human operator. Results are intended to produce data useful in the definition of design and development guidelines/criteria as well as identify technology improvement objectives to enhance overall "teleoperator" system performance.

This final report is intended to present only a brief overview of the study, primarily the objective, approach, and results of each of the six tasks. Each of these tasks have been documented in detail by separate reports, as follows:

Task 1 - MCR 84-511 Issue 1, Task 1 - Define Reference Teleoperator Tasks, January 1984.

Task 2 - MCR 84-511 Issue 2, Task 2 - Define Technology, Development, and Design Options Issues, April 1984.

Task 3 - MCR 84-511 Issue 3, Task 3 - Survey and Assess Previous Studies, Tests, and Experiments, January 1984.

Task 4 - MCR 84-511 Issue 4, Task 4 - Define Missing Elements of Data/Knowledge, May 1984.

Task 5 - MCR 84-512, Task 5 - Human Factors Research Plan, May 1984.

Task 6 - MCR 86-558, Task 6 - Human Factors Research Plan Implementation, May 1986.

1.0 TASK 1 - DEFINE REFERENCE TELEOPERATOR TASKS

1.1 OBJECTIVE

Task 1 focused on the derivation, characterization, and documentation of a set of reference teleoperator tasks that were sufficient in number and scope to be representative of the spectrum of space teleoperation activities likely in the 1985-95 decade. This set was intended to provide a valid representation of critical performance demands on the joint man-machine system. Task complexity, dexterity requirements, and sensing/display requirements are examples of demands reflected in this set.

The emphasis of this Teleoperator Human Factors Study was principally on man/machine interaction issues. To define these issues, it was necessary to develop a thorough understanding and appreciation of the nuances of the overall teleoperator concept configuration as well as the operational tasks involved. Figure 1-1 is a top-level representation of such a system. A more detailed representation is illustrated in Section 1.2, Approach.

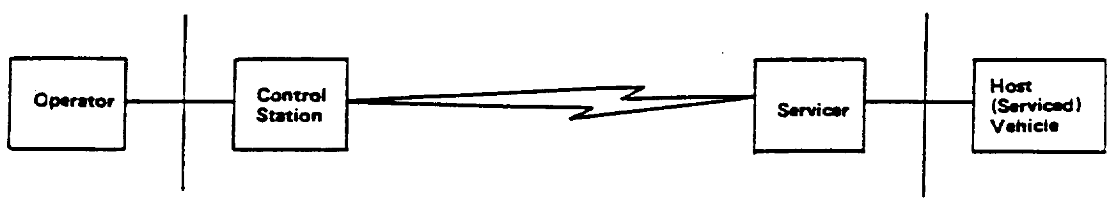

Figure 1-1 Teleoperator System Concept Overview

1.2 APPROACH

The approach selected for Task 1 accomplishment involved detailed (top-down) stairstep decomposition of known and probable sequences from selected missions. Figure 1-2 illustrates this procedure in some detail.

The initial steps in this process involved the development and review of guidelines and constraints and the conduct of studies and reviews to ensure appropriate focus and proper coverage during the study effort. Guidelines and constraints are summarized in Table 1-1.

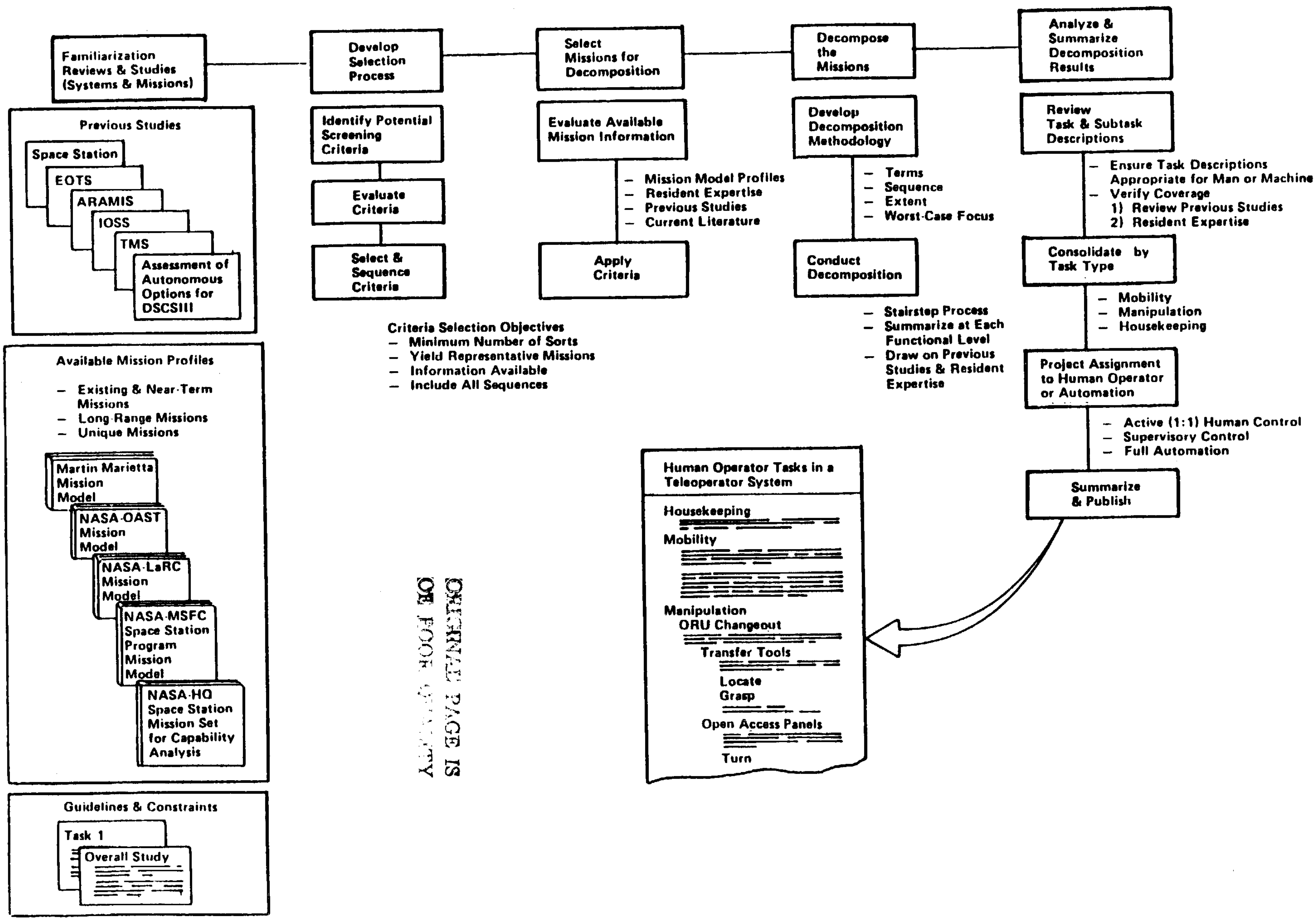

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Figure 1-2 Task 1 Detailed Flow

Table 1-1 Guidelines and Constraints

Study

- Reference tasks are to be used to identify issues that will, in turn, be used to derive test definitions, requirements, and supporting rationale.
- Focus/purpose of study is resolution of critical human engineering issues and characterization of technology effect on performance of remote human operator.

Task 1

- Reference teleoperation task set shall:
  - Be of minimal size (to conserve study resources);
  - Represent the functional spectrum under study, under development, or in use between 1985 and 1995;
  - Encompass mobility control, remote manipulation, and housekeeping functions;
  - Provide valid representation from standpoint of critical performance demands on joint man-machine system;
- Individual tasks/subtasks shall be derived from a combination (composite) of specific planned NASA mission activities and activities of hypothesized, "generic" scenarios.
- Every effort will be made to incorporate results of previous studies (in the interest of efficiency).

Familiarization with relevant systems and missions was ensured by reviewing available mission profiles as well as current and past relevant studies. Examples include ongoing Space Station Studies; Automation, Robotics, and Machine Intelligence System (ARAMIS); Earth-Orbital Teleoperator System (EOTS); Integrated Orbital Servicing System (IOSS); Teleoperator Maneuvering System (TMS); and Assessment of Autonomous Options for the Defense System Communication Satellite (DSCS) III Satellite System.

Mission profiles reviewed are summarized and include our in-house models, the NASA-OAST Model, the NASA LaRC Model, the NASA-MSFC Space Station Program Mission Model, and the NASA-HQ Space Station Capability Analysis Mission Set. Missions in these models covered onorbit vehicles and near-term launches, long-range (probable) missions, and unique missions.

Once these initial steps were completed, attention focused on the review of mission profiles. This involved development of a mission selection method and the subsequent application of that method to identify a satisfactory set of missions for detailed decomposition.

A stairstep sequential decomposition process was used in which common (i.e., redundant) functional groupings at each level were identified through summarization and analysis and then eliminated. This decomposition approach is based on a liberal adaptation of traditional human factors engineering operator-centered analysis practices.

The stairstep sequence-to-subtask decomposition, coupled with analysis of available supporting information (to identify necessary additions to the task/subtask listing), facilitated development of a comprehensive teleoperator task/subtask set. To ensure identification of a comprehensive, if not exhaustive set of reference tasks, both servicer and host vehicle missions were studied. The resulting set, as a group, provides a valid representation of critical performance demands on the joint man-machine system.

One precondition required for successful Task 1 accomplishment was a thorough understanding of the elements and interfaces of the teleoperator system. A two-step approach that drew on resident expertise and early Task 3 findings was used to establish the most likely elements making up such a system and allow definition of the man/machine interfaces involved. Figure 1-1 illustrated the top-level (baseline) system components defined in the first step; Figure 1-3 shows the additional detail developed in the second step.

1.3 RESULTS

1.3.1 Consolidation of Activities

The first step in this summarization process was to compare the activities identified in the scenario decompositions with the activities derived by analysis that were not formally decomposed.

New activities revealed by this screening were then added to the consolidated activity list and carried forward for decomposition to task and subtask level. This comparison was conducted at the activity task and subtask level. This comparison was conducted at the activity level because functions below this level do not have the visibility and clarity required for such an analysis.

1.3.2 Consolidation of Tasks and Subtasks

Two events were involved in this process. New functions identified by inspection were decomposed to reveal the tasks and subtasks involved. These newly identified functions were added to the task or subtask list, as appropriate.

Subsequently, these lists were summarized and edited. The two editorial purposes were to combine identical functions into single-line item entries and to delete those functions that are expected to be highly automated. Many task and subtask level functions were repeated frequently throughout the decomposed scenarios and are expected to be encountered frequently under operational conditions.

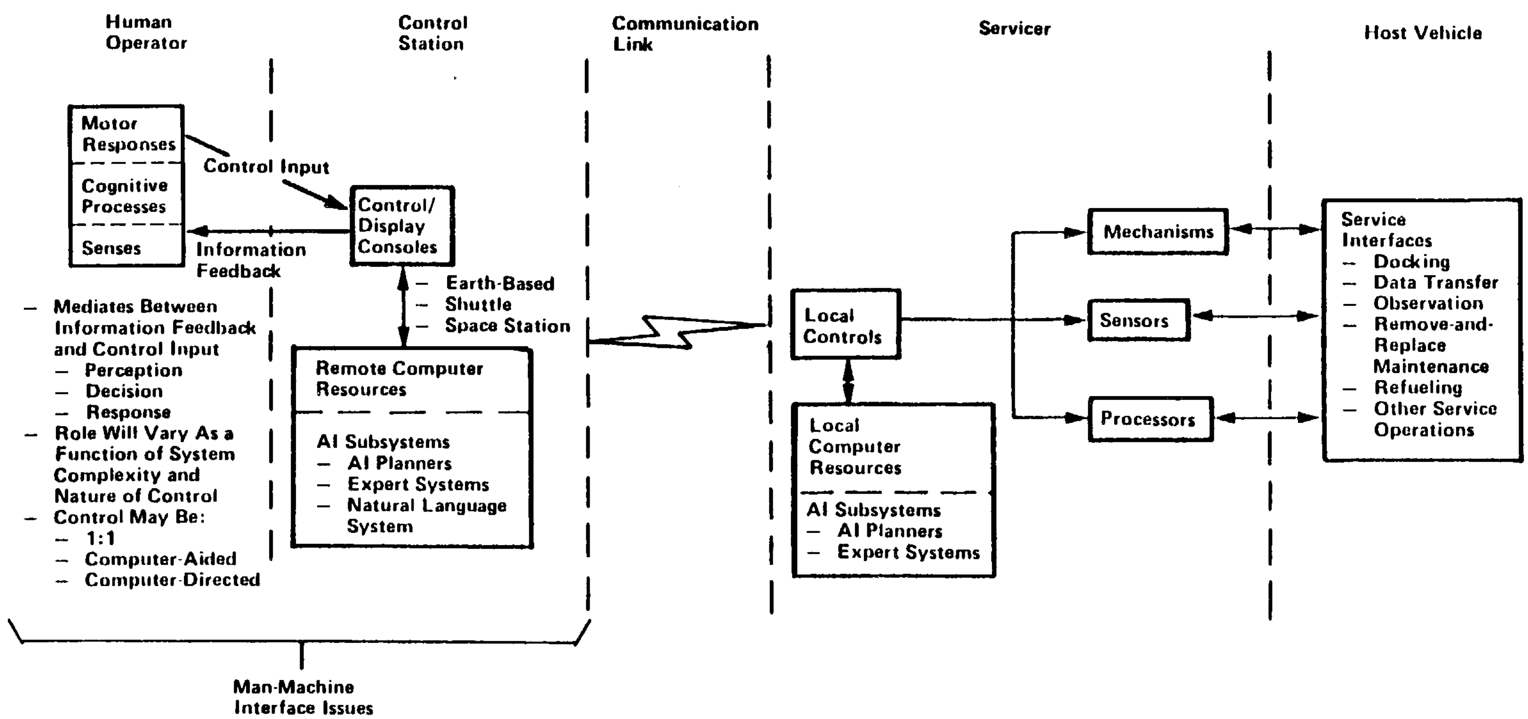

Figure 1-3 Teleoperator System Concept

1.3.3 Critical Performance Demand Analysis

The consolidated functions (tasks and subtasks) from Section 1.3.2 were grouped into three categories:

1) Mobility functions;

2) Manipulation functions;

3) Housekeeping, perceptual, and miscellaneous functions.

These were then integrated into matrices and characterized (scored) in terms of critical performance demands. In scoring each function/demand node, the most stringent requirements encountered were noted.

The critical performance demands that were scored are listed and briefly described below:

1) Repetition - Single versus multiple performance;

2) Definition - Amorphous versus well defined;

3) Archival Information Needs - Small amount, quantitative versus large volume, qualitative;

4) Duration - Short lived versus long lived;

5) Sensing, Tactile - Little use versus heavy use;

6) Sensing, Visual - Little use, low resolution versus heavy use, high resolution;

7) Dexterity - Few degrees of freedom versus many degrees of freedom;

8) Task Complexity - Simple, straightforward versus multidimensional, convoluted;

9) Precision - Gross skills versus high tolerance;

10) Engineering Data - Simple measurements, small amount of calculation versus complex measurements, large amount of measurements and/or calculations.

The three resulting matrices appear in Tables 1-2 through 1-4. Those function/demand nodes that received a high (3) rating derive requirements for specific teleoperator functions. They were discussed in detail in the Task 4 report if they were related to voids identified. As necessary, the discussion of these functions continued in the research plan development process (Task 5).

Table 1-2 Critical Performance Demands of Mobility Functions

CRITICAL PERFORMANCE DEMANDS / MOBILITY FUNCTONS	REPETITION	LACK OF DEFINITION	ARCHIVAL INFO REQ	DURATION	SENSING: TACTILE	SENSING: VISUAL	SENSING: OTHER	DEXTERITY	TASK COMPLEXITY	PRECISION REQUIRED	ENGINEERING DATA
Adjust Approach Direction	3	1	2	2	-	3	3	-	1	2	1
Adjust Approach Velocity	3	1	2	2	-	3	3	-	1	2	1
Align Probe with Target	2	1	2	2	-	3	-	-	2	3	1
Create Delta V (Push Off)	2	1	1	1	-	1	-	-	1	1	1
Establish Contact Between Probe and Target	2	1	1	2	2	1	1	-	2	3	1
Establish Interface for Transit	1	1	3	2	2	2	1	-	2	2	1
Execute Burn (Main Motor or ACS Thrusters)	3	1	1	1	-	-	-	-	1	2	1
Position OMV (with/without Deployable Component)	1	1	2	2	-	3	3	-	2	2	1
Synchronize OMV Dynamics to Host S/C Dynamics	1	1	3	3	-	3	3	-	3	3	3

\- = N/A or requirement not defined 3 = High; 2 = Moderate; 1 = Low

Table 1-3 Critical Performance Demands of Manipulation Functions

CRITICAL PERFORMANCE DEMANDS / MANIPULATION FUNCTIONS	REPETITION	LACK OF DEFINITION	ARCHIVAL INFO REQ	DURATION	SENSING: TACTILE	SENSING: VISUAL	SENSING: OTHER	DEXTERITY	TASK COMPLEXITY	PRECISION REQUIRED	ENGINEERING DATA
Adjust Fastener Tension (Turn)	1	1	1	1	3	-	-	1	1	3	1
Break Free Fastener (Turn)	1	1	1	1	3	-	-	1	1	2	1
Disconnect Umbilical (Turn)	2	1	1	1	2	2	-	2	1	2	1
Disconnect ORU (Turn)	2	2	2	2	2	2	-	2	2	2	2
Extend/Retract Umbilical	2	2	1	1	2	1	-	-	1	1	1
Fasten (Attach) ORU	2	2	1	1	2	2	-	2	1	2	1
Grapple Target on Host S/C	1	3	3	1	2	2	-	2	3	2	2
Grasp Target Item	3	3	2	1	2	2	-	3	2	2	1
Move to Target Vinicity	3	1	2	2	-	3	3	-	2	2	2
Place (Final) Item	3	1	2	2	2	3	-	3	2	3	2
Position (Rough) Item	3	1	1	1	-	2	-	2	1	1	1
Recover (Index) Manipulator(s)	3	1	1	1	1	2	-	1	1	3	2
Release Grasp	3	1	2	1	2	2	-	2	2	1	1
Restrain (Secure) Panel	2	2	2	1	1	2	-	2	1	2	1
Secure Item	3	2	1	1	2	2	-	2	2	2	1
Transfer Item to Destination	3	1	2	2	-	3	-	-	2	2	2
Turn Clockwise/Counterclockwise	1	1	2	1	2	2	1	2	1	2	1

\- = N/A or requirement not defined 3 = High; 2 = Moderate; 1 = Low

Table 1-4 Critical Performance Demands of Housekeeping, Perceptual, and Miscellaneous Functions

CRITICAL PERFORMANCE DEMANDS	REPETITION	LACK OF DEFINITION	ARCHIVAL INFO REQ	DURATION	SENSING: TACTILE	SENSING: VISUAL	SENSING: OTHER	DEXTERITY	TASK COMPLEXITY	PRECISION REQUIRED	ENGINEERING DATA
HOUSEKEEPING, PERCEPTUAL, AND MISCELLANEOUS FUNCTIONS											
Activate/Deactivate System	3	1	1	1	-	-	-	-	1	-	2
Analyze Alternatives	3	1	3	2	-	-	-	-	3	-	3
Assess Host S/C Dynamics	2	1	3	1	-	3	3	1	3	3	-
Choose Optimal Control Mode(s)	2	1	2	1	-	-	-	-	3	-	1
Choose Optimal Trajectory	1	1	2	1	-	-	-	-	3	-	1
Collect Data	1	2	1	1	-	-	3	-	1	-	1
Compare Observations/Data to Model	3	1	1	2	-	-	-	-	2	3	3
Decide Whether to Revise Mission Profile or Reallocate Consumable(s)	2	2	2	2	-	-	-	-	3	-	1
Deploy Capture Device	2	1	1	2	-	1	1	1	1	1	1
Determine Amount, Direction (and Timing) of Necessary Change(s)	3	1	3	2	-	-	-	-	3	3	1
Determine Current Conditions (Sensor Function)	3	1	1	1	-	-	3	-	2	-	3
Determine Difference Between Current and Desired Conditions	3	1	2	1	-	-	-	-	1	3	-
Effect Adjustment(s)	3	1	1	2	2	2	3	2	2	3	3
Enable Activation/Deactivation	2	1	1	1	-	-	-	-	1	-	-
Evaluate Subsystem Performance	3	1	2	3	-	2	2	1	3	3	3
Fine Focus Detector	1	1	1	2	-	-	3	-	2	3	1
Identify (Select) Target Item/Area	3	1	3	2	3	3	-	-	3	-	-
Locate Destination/Target	3	1	3	2	3	3	-	1	3	2	-
Lock/Unlock Docking Mechanism	2	1	1	1	-	-	-	-	1	-	1
Observe Process (Script)	2	2	1	2	-	3	3	1	3	-	1
Observe S/C Condition and Configuration/Process Result	2	1	1	2	-	3	3	2	3	-	1
Operate Sensor(s)	1	1	2	3	-	-	-	-	3	-	1
Revise Mission Profile	1	1	3	2	-	-	-	-	1	-	-
Select From Among Alternatives	3	1	3	3	-	3	2	1	3	-	2
Switch Off/On Selected Subsystem/Initiate Process	1	1	1	1	-	-	-	-	1	-	-
Verify Action Completed Satisfactorily	3	1	2	1	-	3	3	1	1	-	1

- = N/A or requirement not defined   3 = High; 2 = Moderate; 1 = Low

2.0 TASK 2 - DEFINE TECHNOLOGY, DEVELOPMENT, AND DESIGN OPTIONS ISSUES

2.1 OBJECTIVE

The objective of Task 2 was to define for each Task 1 reference task the technology/development/design options, issues, and/or alternatives that involve an effect on human operator performance as an element of the teleoperator control system. In addition, a composite list (eliminating redundant items), suitable as a frame of reference for activity described in Tasks 3, 4, and 5, was to be established.

2.2 APPROACH

The original approach to Task 2 required the Reference Task Set from Task 1 before initiation. However, by using data from Task 3 (survey and assessment of previous studies, tests, and experiments), which was performed concurrently with Task 1, a preliminary issues list was generated based on the review of previous teleoperator studies data. The process flow is shown in Figure 2-1. This preliminary issues list was categorized into eight general areas and the potential issues subcategorized appropriately under each general area.

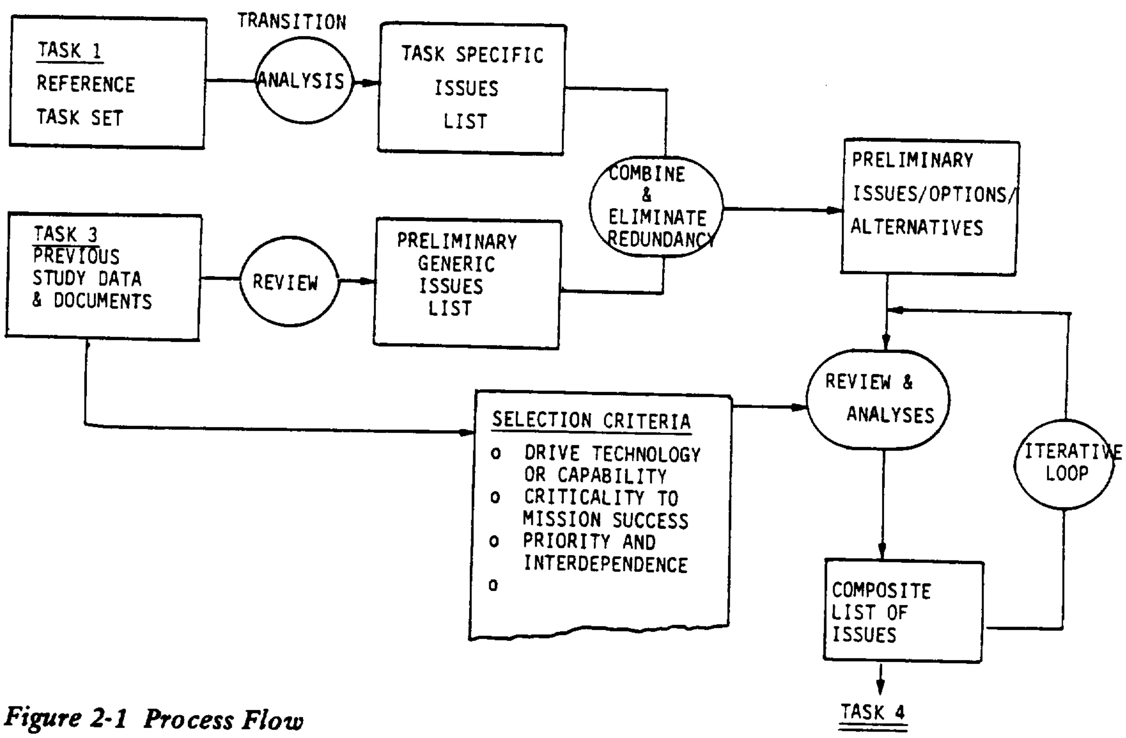

Figure 2-1 Process Flow

At the completion of the Task 1 mission analysis, the Reference Task Set was reviewed and subtasks analyzed for commonality of system work elements. (Work elements are defined as identifiable increments of a subtask, which in turn is made up of discrete primitive actions.) To simplify and eliminate redundancy, these work elements (Table 2-1) were reduced to the fewest possible and all system actions with similar functions were grouped together and common terminology applied.

Table 2-1
Transition Process for Operator Requirements

Work Element	Mobility	Manipulation	Information Management
Start/Stop	X	X	
Identify			X
Locate	X	X	
Orient		X	
Translate	X		
Transfer		X	
Contact	X	X	
Align		X	
Grasp		X	
Adjust		X	
Fasten		X	
Check			X

The work elements were further broken down into primitive actions, Table 2-2, which were considered to be the most basic increments and, therefore, the most representative of teleoperation activities with little dependence upon mission specific requirements. The primitive actions for each work element for mobility, manipulation, and information management were then analyzed for alternative means of implementation and the potential human operator effects.

Table 2-2 Activity Condensation

	Mobility					Manipulation									
Primitive Actions	Start/Stop	Locate	Orient	Translate	Contact	Start/Stop	Locate	Transfer	Contact	Grasp	Align	Adjust	Fasten	Info Mgmt	Measurement
Establish Reference	X		X	X		X		X			X			X	
3-DOF Rotation															Rotation
Pitch (Tilt	X		X			X		X			X	X	X		
Yaw (Scan)	X	X	X			X	X	X			X	X	X		
Roll	X	X	X			X	X	X			X	X	X		Distance
3-Axis of Linear Motion															Time
Up/Down (±Y)	X			X		X		X				X	X		Velocity
Left/Right (±X)	X			X		X		X				X	X		Acceleration/ Deceleration
Forward/Backward (±Z)	X			X		X		X				X	X		(0.1)
Power Status: On/Off	X					X				X	X	X	X		
Hold														X	
Signal Detection & Proc	X				X	X			X	X		X	X		Force/Torque
Touch															Mass.
Vision															Center of Gravity

This list of human operator effects was then combined with the preliminary issues list generated earlier, and the listing screened for redundancy. This Potential Issues List is provided in the expanded outline on pages vi through xi and discussed in further detail in the Task 2 report. This Potential Issues List was provided as inputs to Tasks 3 and 5 of this study to initiate their activities before completion of the final composite list.

Each of these potential issues was then examined in terms of the criteria discussed below and the importance and significance documented. Potential issues were eliminated from further consideration and discussion in subsequent study tasks if the item did not exhibit clear relevance to either the Reference Task Set (Task 1) or the anticipated requirements of general (generic) teleoperation activities. The issues that related to rapidly advancing technology areas were retained for further examination of options/alternatives and potential operator impacts. These technology areas included sensors, automation techniques, machine intelligence, display and control methods, end-effectors, and manipulators, all of which will potentially redefine the role of the human operator. Any issue that considered potential enhancement of teleoperation activities (near-term or future) was retained for further review.

2.3 RESULTS

The detailed teleoperator system concept presented in Section 1.0 herein, indicated six major elements inherent within the concept. By inclusion of overall system considerations and data processing, with other slight redefinitions, the concept was readily adaptable to an outline for the teleoperation issues categories. This outline is shown in Table 2-3.

The composite issues list was structured in accordance with that outline. The detailed listing, which was used in the performance of the subsequent tasks in this study, is included in the Appendix as further modified during Task 5 activities.

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.0 SPACE SYSTEMS

5.1 Mechanisms
- 5.1.1 Actuators
  - .1 Electromechanical
  - .2 Hydraulic
  - .3 Pneumatic
- 5.1.2 Structure
  - .1 Dimensional Information
    - Shape
    - Length
    - Configuration
  - .2 Materials
- 5.1.3 End Effectors (EE)
  - .1 Two Opposing Fingers
  - .2 Multi Fingered Hand (3 or more)
  - .3 Replaceable EE (Special Tools)
- 5.1.4 Manipulators
  - .1 5 or Less DOF
  - .2 6 or More DOF
  - .3 Anthropomorphic
- 5.1.5 Docking Devices
  - .1 Impact Docking
  - .2 Non-Impact Docking
- 5.1.6 Module Attachment
  - .1 Direct (Two or More Points)
  - .2 Transition Devices
  - .3 Other Methods
- 5.1.7 Structure Attached Mobility
  - .1 Cable
  - .2 Rail

5.2 Sensory Perception Devices
- 5.2.1 Vision Imaging Sensors (Indirect)
  - .1 Video Cameras
  - .2 Non-Video Lasers
- 5.2.2 Intraoceptive Sensors
  - .1 Limit Switches
  - .2 Position Transducers
  - .3 Speed Transducers
  - .4 Force/Torque
  - .5 Temperature
- 5.2.3 Extraoceptive Sensors
  - .1 Touch/Feel and Force
  - .2 Temperature

5.3 Data Handling

5.4 Control Modes
- 5.4.1 Automation and AI
- 5.4.2 Coordinated Multi Arm
- 5.4.3 Camera Unit
- 5.4.4 Hierarchical
- 5.4.5 Adaptive

5.5 Space Robotics Tasks
- 5.5.1 Manipulation
- 5.5.2 Mobility

5.6 Space Qualification
- 5.6.1 Environments
- 5.6.2 Degree of Verification

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6.1 Attachment
- 6.1.1 Docking
  - .1 Impact Docking
  - .2 Non-Impact Docking
- 6.1.2 Material Handling
  - .1 Hold Points
    - Prepared vs Primitive
  - .2 Grip Points
    - Single vs Dual Hand
- 6.1.3 Module Mounting
  - .1 Direct Multi-Attach Points
  - .2 Standard Interface Module (Two Release/Attach Points)
  - .3 Flexible Transition Module (One Release/Attach Point)
- 6.1.4 Mobility on/or in Structure
  - .1 Captive Track/Cable/Rail
  - .2 Mass Propulsion

6.2 Lighting
- 6.2.1 Solar Lighting
  - .1 Surface Finish
  - .2 Mechanical Filters
- 6.2.2 Artificial Lighting
  - .1 Types and Intensities
  - .2 Number and Mounting Locations
  - .3 Control
- 6.2.3 Low Level Lighting Techniques

6.3 Degree of Autonomy
- 6.3.1 Conventional Automation
  - .1 Computation/Control (Onboard vs Ground)
  - .2 Onboard Redundancy
- 6.3.2 Flexible Automation
  - .1 Teleoperation (Human Interaction)
  - .2 On-line Programming
  - .3 Expert System

6.4 Rigidity/Stability
- 6.4.1 Hardware Stiffness
  - .1 Design Stiff Components
  - .2 Minimize Number of Active Interfaces
- 6.4.2 Dynamic Event Modeling

6.5 Degree of Structure (Serviceability)
- 6.5.1 Serviceability Levels
- 6.5.2 Spacecraft Design Standardization
- 6.5.3 Impacts of Highly Structured Worksite
  - .1 Design/Build Cost Tradeoff (Servicer vs Worksite)
  - .2 Operational Complexity Tradeoffs

6.6 Module/Component Interface
- 6.6.1 Storage Rack Considerations
- 6.6.2 Changeout Characteristics
- 6.6.3 Interface Connectors

6.7 Other Areas
- 6.7.1 Host Spacecraft Services
- 6.7.2 Test Ports

7.0 TASK

7.1 Information Requirements
- 7.1.1 Collection (Sensors)
- 7.1.2 Processing/Enhancement
- 7.1.3 Presentation

7.2 Critical Performance Demands
- 7.2.1 Repetiton
- 7.2.2 (Lack of) Definition
- 7.2.3 Archival Information Required
- 7.2.4 Duration
- 7.2.5 Sensing:
  - Tactile
  - Visual
  - Other
- 7.2.6 Dexterity
- 7.2.7 Task Complexity
- 7.2.8 Precision Required
- 7.2.9 Engineering Data Required

7.3 Degree of Structure
- 7.3.1 Working Envelopes (Motion Limits)
- 7.3.2 Coding and Position Reference Aids
- 7.3.3 Primitive Operations
- 7.3.4 Conventions

7.4 Task Development
- 7.4.1 Task Panel Definition
  - .1 Environmental Variables
  - .2 Nature of Task
  - .3 Nature of Issue(s) of Interest
- 7.4.2 Experimentation (Task Panel Use)
  - .1 Specifications
  - .2 Integration of Lessons Learned
  - .3 Treatment of Time Delay

8.0 SYSTEM CONSIDERATIONS

8.1 Subsystem Arrangements
- 8.1.1 Control Station
  - .1 Ground Based
  - .2 Space Based
- 8.1.2 Space System

8.2 Overall System Intelligence
- 8.2.1 Information Management
- 8.2.2 User Compatibility
  - .1 Natural Language Interface
  - .2 Speed of Resonse
- 8.2.3 Failure
  - Detection
  - Isolation
  - Recovery

8.3 Design Constraints
- 8.3.1 System Life
  - .1 Operational
  - .2 Repair/Refurbish

8.4 Programmatic Considerations
- 8.4.1 Commonality
- 8.4.2 Reliability
- 8.4.3 Maintainability
- 8.4.4 Producibility
- 8.4.5 Safety

8.5 Tech Development Implementation
- 8.5.1 Software Architecture
- 8.5.2 Output Hardware Upgrade/Reconfiguration

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Table 2-3 Teleoperation Issue Categories

1.0 HUMAN OPERATOR

- 1.1 Anthropometry and Biomechanics
  - 1.1.1 Anthropometric Data
  - 1.1.2 Biomechanics Data
- 1.2 Perceptual Capabilities/Interfaces
  - 1.2.1 Vision (direct vs indirect)
    - .1 Target
      - Detection
      - Tracking
      - Identification
    - .2 Stereo/Mono
    - .3 B&W/Color
  - 1.2.2 Audition
    - .1 Tonal
    - .2 Speech
  - 1.2.3 Somesthetic
  - 1.2.4 Kinesthetic
  - 1.2.5 Other Considerations
    - .1 "ESP"
    - .2 Cross-sensory Interaction
- 1.3 Central Processes
  - 1.3.1 Decision Making
  - 1.3.2 Information Processing
    - .1 Assimilation Rate
    - .2 Capacity
  - 1.3.3 Memory
    - .1 Sensory Information Storage
    - .2 Short Term Memory
    - .3 Long Term Memory
  - 1.3.4 Other Considerations
    - .1 Feedback Time Delay
    - .2 Cognitive Limitations
    - .3 Stress Spectrum
    - .4 Technology Acceptance
- 1.4 Performance Characterization
  - 1.4.1 Motor-Perception
    - .1 Sensitivity
    - .2 Dexterity
    - .3 Reaction Time
    - .4 Tracking
  - 1.4.2 Work Capacity/Strength
    - .1 Body Motions
    - .2 Dynamic Forces
    - .3 Static Forces
  - 1.4.3 Human Constraints
    - .1 Work-Rest Cycle
    - .2 Learning
      - Assimilation Rate
      - Capacity
    - .3 Training
    - .4 Stress
    - .5 Sleep
- 1.5 Operator Pool Characterization and Selection Criteria
  - 1.5.1 Aptitude (Testing/Trainability)
    - .1 Perceptual Talents
    - .2 Psychomotor Skills (Dexterity, etc.)
  - 1.5.2 Biographical Data
    - .1 Geographical Location
      - Accessibility
      - Availability
    - .2 Educational Background
    - .3 Work Experience
      - Astronaut
      - Nuclear Industry
      - Pilot (RPVs)
      - Scientist
      - Technician
  - 1.5.3 Physical Capabilities (Work Capacity/Strength)
    - .1 Body Movement
    - .2 Strength
      - Dynamic
      - Static
    - .3 Anthropometry
    - .4 Age
    - .5 Gender
  - 1.5.4 Physiological
    - .1 Endurance
    - .2 Resistance to Stress
    - .3 Biorhythm Disruption Tolerance
  - 1.5.5 Psychological
    - .1 Personality Trait
    - .2 Stress Tolerance
    - .3 Skills Inventory
    - .4 Decision-making Style
    - .5 Piloting Style
- 1.6 Work/Task Analysis
  - 1.6.1 Man-Machine Function Allocation
  - 1.6.2 Number of Operators
  - 1.6.3 Operator Role Assessment

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- 2.1 Architectural/Ergonomics
  - 2.1.1 Gross Station Layout
  - 2.1.2 Operator Workstation Interfaces
  - 2.1.3 Environmental Impacts
  - 2.1.4 Qualification
- 2.2 Display Elements (output)
  - 2.2.1 Static Displays
  - 2.2.2 Dynamic Instruments
  - 2.2.3 Monitors
  - 2.2.4 Space Similar Hardware
  - 2.2.5 Advanced CRTs
  - 2.2.6 Flat Panel Displays
  - 2.2.7 Auditory Displays
- 2.3 Command Mechanisms (input)
  - 2.3.1 Conventional Control Movements
  - 2.3.2 Discrete Input Devices
  - 2.3.3 Limited DOF Input Devices
  - 2.3.4 Multi DOF Input Devices
  - 2.3.5 Gesture Detection Devices
  - 2.3.6 Voice Recognition/Synthesi
  - 2.3.7 Eye Tracking
- 2.4 Integration of C&D Items
  - 2.4.1 Functional Grouping
  - 2.4.2 Control-Display Ratios
  - 2.4.3 Control Station Flexibility
- 2.5 Communication of Task Semantics
  - 2.5.1 Human Error Impacts
  - 2.5.2 "User Friendly" Techniques

3.0 PROCESSING

- 3.1 Hardware Selection
  - 3.1.1 Increased Computing Required
    - .1 Semiconductor Advancements
    - .2 Parallel Processing
    - .3 Super Computers
  - 3.1.2 Mass Memory Needs
    - .1 Magnetic Tapes
    - .2 Bubble Memory
    - .3 Optical Disks
  - 3.1.3 Fault Tolerant Hardware
- 3.2 Software Selection
  - 3.2.1 Language (ADA, LISP, etc)
  - 3.2.2 Architecture (Conventional vs Intelligent)
  - 3.2.3 Fault Tolerant Software
    - .1 Modular Decomposition
    - .2 Atomic Actions
    - .3 Exception Handling
    - .4 Hybrid Plus Others
- 3.3 Location (Ground vs Space)
  - 3.3.1 Operational Methods
    - .1 Man Intensive
    - .2 Supervisory
    - .3 Automation
  - 3.3.2 Time Delays
    - .1 Real Time Computing
    - .2 Expert Systems
    - .3 Path Planning
    - .4 Adaptive Control
  - 3.3.3 Life Cycle Costs
    - .1 Ground vs Flight Qual
    - .2 Computer Aided Control
    - .3 Front-end vs Cost Delay
    - .4 Personnel Reductions
- 3.4 Degree of Autonomy
  - 3.4.1 Autonomy Feasibility Level
    - .1 Flexible Automation
    - .2 Teleoperation
  - 3.4.2 Human Interaction/Override Capability
    - .1 Expert System
    - .2 Limit Techniques (Hardware or Software)

4.0 COMMUNICATIONS

- 4.1 Real Time
  - 4.1.1 Tracking and Data Relay System (TDRS)
    - .1 Continuous Operations
    - .2 Segmented Operations
  - 4.1.2 STDN
  - 4.1.3 Shuttle Orbiter
- 4.2 Time Delay
  - 4.2.1 Magnitude Variations
    - .1 Nature of Delays
    - .2 Alternatives
  - 4.2.2 Effects of TD
    - .1 System Design
    - .2 Human Operator Interactions
- 4.3 Information Bandwidth
  - 4.3.1 Data Types
    - .1 Uplink Commands
    - .2 Downlink Data (Engineering and Sensory)
  - 4.3.2 Video Imaging
    - .1 Stereo vs Mono
    - .2 Color Imaging
    - .3 Performance Factors
- 4.4 Data Handling

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3.0 TASK 3 - SURVEY AND ASSESS PREVIOUS STUDIES, TESTS, AND EXPERIMENTS

3.1 OBJECTIVE

The Task 3 objective was to identify and survey previous man-in-the-loop (MITL) studies, tests, and experiments. The data were to include a compilation of the investigations, together with appropriate identifying information, and an assessment of the contents. The overall purpose of this task was to provide information contributing to an understanding of the composite list of items derived in Task 2 for assessment in Task 4.

3.2 APPROACH

This effort was divided into two basic parts (1) to identify previous man-in-the-loop studies, and (2) collect literature into a human factors database as well as assess the contents of the base to assist in the performance of Task 4, Define Missing Elements of Data/Knowledge, regarding human factors issues about teleoperation.

The detailed approach depicted in Figure 3-1 was created to pursue the Task 3 effort in a logical, systematic, top-down progression of events resulting in a comprehensive literature database of past human factors studies, test, and experiment results. This database will be used in Task 4 as a comparison base along with the technology and development issues enumerated in Task 2 to identify information voids that future human factors research need to pursue and fill. By starting with the acknowledged "experts", reference texts, and extracting their bibliographies, we felt we had the best initial base of literature that was available as of the publication date of each text. We realize that the more recent a listing is, the more current research it contains and will reflect improvements or possibly completely new results in each topical area examined.

The key words and phrases extracted as the research continued were significant as discriminators for selecting the appropriate documents to reside in the database. Additionally, while screening the results of computer-based literature searches conducted by others, a comparison of the key word list for the literature search with our own list contributed to the credibility of the search. The most recent search conducted by others was dated June 1982, and had approximately 80% correlation in the key work/phrase lists (Table 3-1) comparison.

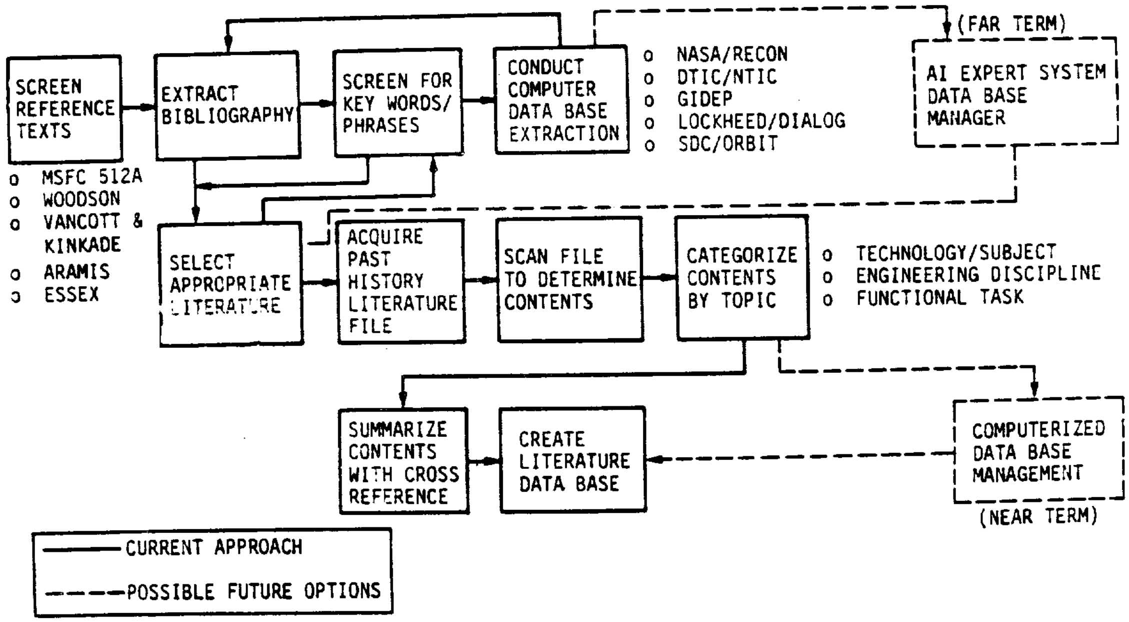


Figure 3-1 Research Approach

Table 3-1 Literature Search Keywords/Phrases

CONTROL STATION		COMMUNICATIONS	SPACE ACTIVITIES	INTERFACES
HUMAN ELEMENT	EQUIPMENT ELEMENT			
*HUMAN FACTORS	CONTROLS	REMOTE CONTROL	*MANIPULATION	*MAN-MACHINE
HUMAN ENGINEERING	DISPLAYS	REMOTE MANNED	MOBILITY	MASTER-SLAVE
	AUDITORY CUING		MANEUVERING	
	VISUAL CUING		*REMOTE MANIPULATION/ MANIPULATOR	
	FORCE/TORQUE FEEDBACK		REMOTE SENSING	
			REMOTE PILOT/ PILOTING	
			FREE FLYER/FREE FLYER CONTROL	
OVERALL SYSTEM			*ROBOT/ROBOTIC	
*TELEOPERATOR/TELEOPERATION			ANTHROPOMORPHIC DEVICES	
TASK/FUNCTION ALLOCATION			DOCKING MECHANISM	
TELEPRESENCE			END EFFECTORS	
*ERGONOMICS				
*AUTOMATA				

*ACTUAL KEYWORDS USED FOR DTIC SEARCH

As we commenced evaluating the literature available on the subject of human factors in teleoperations, we quickly learned the volume of literature was so great that some partitioning or division of material was necessary. We then determined that three major divisions were sufficient to provide the necessary separation. The major divisions are as follows:

1) Human Factors Standards and Specifications (NASA/DOD);

2) Human Factors Reference Texts (quoted experts, "bibles");

3) Human Factors Studies, Tests, Experiments Reports, Papers, and Dissertations.

The main thrust of the literature search and database accumulation was to discover and analyze these reports and papers that truly chronicle the results of meaningful human factors research conducted in the past. To preclude "reinventing the wheel" in future research, we intended to compare what has already been determined to factors necessary to advance human factors knowledge in the field of teleoperations. We have identified standards and specifications plus reference texts predominately to reflect knowledge of their existence, realizing that they are the compilations of the best available knowledge on human factors in general as of their respective publication dates. Therefore, to prevent confusion we will list here those standards, specifications, and reference texts that apply to this effort, leaving the literature list to reflect the actual research reports and papers.

Human Factors Standards/Specifications:

Marshall Space Flight Center Design Standard 512A: Man/System Requirements for Weightless Environment. December 1976.

Military Standard 1472C: Human Engineering Design Criteria for Military Systems, Equipment, and Facilities. May 2, 1981.

Department of the Air Force/AFSC Design Handbook 1-3: Human Factors Engineering. Third Edition, Revision 1, June 25, 1980.

Reference Texts:

W. E. Woodson: Human Factors Design Handbook. McGraw and Hill, 1981.

H. P. VanCott and R. G. Kinkade: Human Engineering Guide to Equipment Design. Ames Institute of Research, Washington, DC, 1972.

A. Chapanis: Man-Machine Engineering. Wadsworth Publishing Co., Inc., Belmont, CA, 1965.

B. Schneiderman: Human Factors in Computer and Information Systems. Winthrop Publishers.

Literature Sources:

The reference texts cited above satisfied a secondary function. Their respective bibliographies provided a lucrative source of pertinent human factors literature. Therefore, our initial approach to Task 3 was to screen the bibliographies of each reference texts. Then as each additional piece of literature was screened, its bibliography was added to the source base for future screening. This method of gathering source material is fairly comprehensive, however, it is very time consuming. Therefore, at some point, the decision was made to terminate the gathering aspect and begin organizing and assessing the literature search efforts.

3.3 RESULTS

More than 400 literature sources were identified. These sources were reviewed and coded to indicate what technology and development issues they examined. The data sources were then organized into matrices according to author and government/industry sources, along with the required identifying information. The database was then supplemented with cross references. Refer to the Task 3 report for the detailed listings.

A summary of the literature distribution with respect to the teleoperation subject categories developed in Task 2 is shown in Table 3-2. The distribution of citations assigned to each subject category gave the first indication of probable information voids, a subsection of Task 4. The large number of citations appearing at the top level of each set of subsection groupings are "unassigned". These documents were identified in the search process, but neither copies nor abstracts sufficiently detailed to permit more specific subject identification could be obtained within the study constraints. The overall totals exceed the number of sources; some sources were applicable to more than one category.

Table 3-2 Literature Distribution

Teleoperation Subject Categories	Number of Citations	
1.0 HUMAN OPERATOR	60	
1.1 Anthropometry and Biomechanics		1
1.2 Perceptual Capabilities/Interfaces		36
1.3 Central Processes		12
1.4 Performance Characterization		26
1.5 Operator Pool Characterization and Selection		5
1.6 Work/Task Analysis		33
2.0 CONTROL STATION	49	
2.1 Architectural/Ergonomics		17
2.2 Display Elements (output)		33
2.3 Command Mechanisms (input)		16
2.4 Integration of C&D Items		8
2.5 Communication of Task Semantics		5
3.0 PROCESSING	20	
3.1 Hardware Selection		0
3.2 Software Selection		4
3.3 Location (Ground vs Space)		3
3.4 Degree of Autonomy		6
4.0 COMMUNICATIONS	20	
4.1 Real Time		5
4.2 Time Delay		17
4.3 Information Bandwidth		3
4.4 Data Handling		2
5.0 SPACE SYSTEMS	141	
5.1 Mechanisms		34
5.2 Sensory Perception Devices		22
5.3 Data Handling		11
5.4 Control Modes		42
5.5 Space Robotics Tasks		46
5.6 Space Qualification		3
6.0 WORK SITE	52	
6.1 Attachment		11
6.2 Lighting		5
6.3 Degree of Autonomy		4
6.4 Rigidity/Stability		1
6.5 Degree of Structure (Serviceability)		3
6.6 Module/Component Interface		2
6.7 Other Areas		27
7.0 TASK	34	
7.1 Information Documents		2
7.2 Critical Performance Demands		0
7.3 Degree of Structure		2
7.4 Task Development		0
8.0 SYSTEM CONSIDERATIONS	27	
8.1 Subsystem Arrangements		3
8.2 Overall System Intelligence		3
8.3 Design Constraints		6
8.4 Ility Considerations		1
8.5 Technology Development Implementation		1

4.0 TASK 4 - DEFINE MISSING ELEMENTS OF DATA/KNOWLEDGE

4.1 OBJECTIVE

Task 4 had as its central purpose the definition of the additional (missing) information necessary to accomplish the objective described in the scope of work. This additional information was to be derived from the composite list compiled in Task 2 by consideration of the contributing data identified in Task 3. Specifically, it was to generate definitions, requirements, and supporting rationale for a set of investigations intended to do the following:

1) Resolve critical human engineering issues;

2) Characterize the effects of various design/development options and incremental technology advancements on the performance of the remote human (controller) element of the teleoperator system.

4.2 APPROACH

This process took place in two parts as depicted in Figure 4-1. Missing information (voids) was identified and, where appropriate, compared against projected state-of-the-art advancement(s). These voids were identified by comparing available prior study information (Task 3) against the issues, options, and/or alternatives list developed in Task 2 (reference Fig. 2-1). The purpose of this information void determination effort was to use the voids identified to focus research relevant to the teleoperations field, that is, to define the direction and depth necessary for future tests, experiments, and analyses.

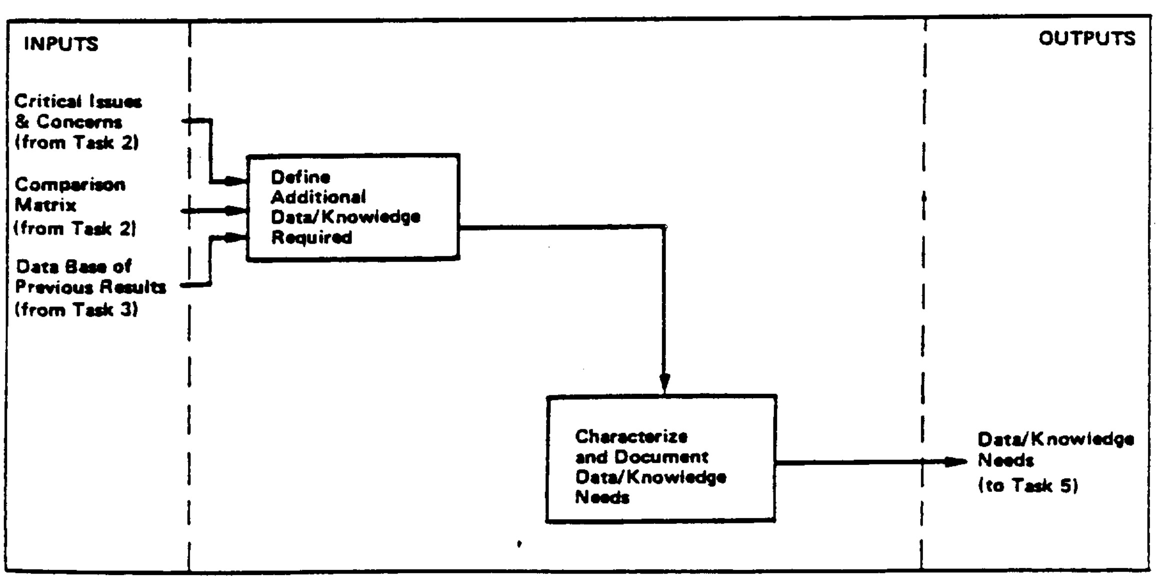


Figure 4-1 Task 4 Information Flow

These voids were then characterized in terms of the required tests, experiments, and/or analyses. The characterizations, in turn, were fully developed in Task 5, the Teleoperator Human Factors Research Plan.

Figure 4-2 presents an overview of this process.

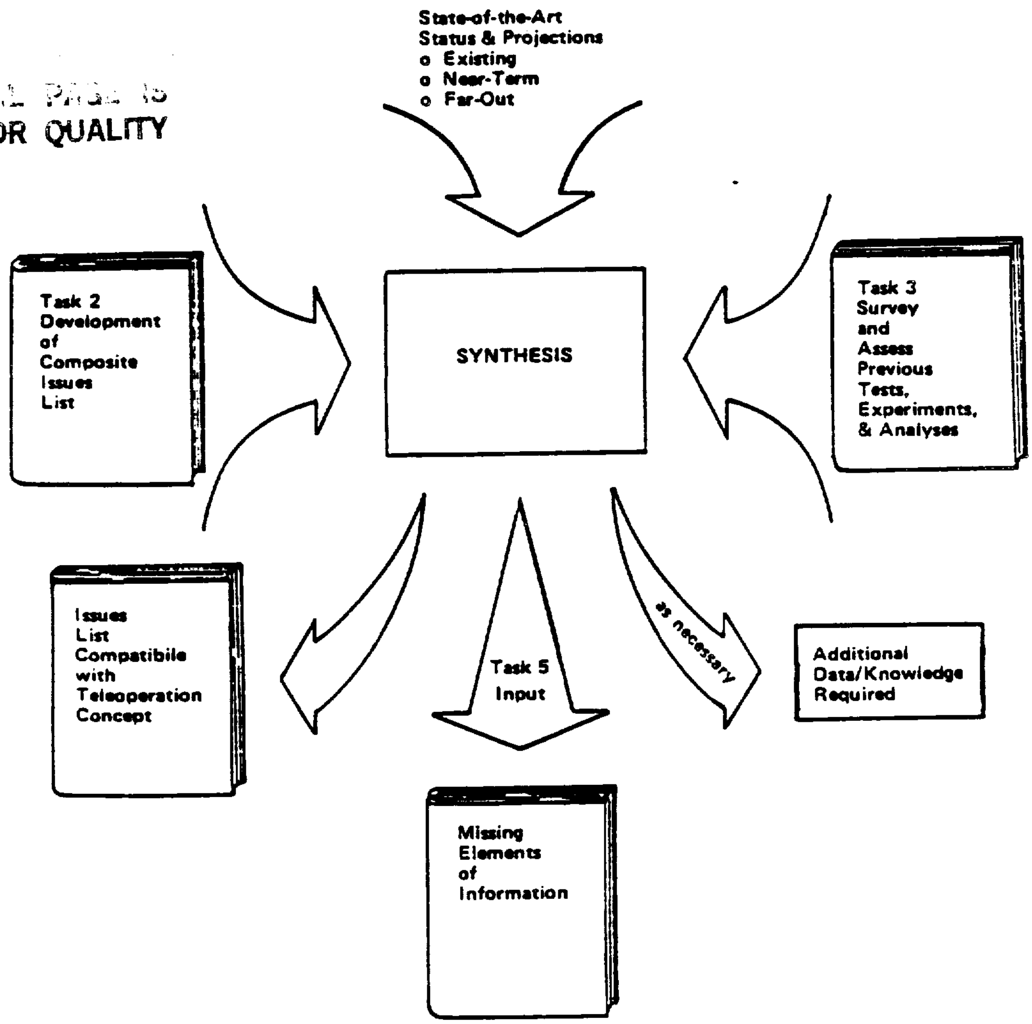


Figure 4-2 Task 4 Overview

4.3 RESULTS

A summary assessment combined the information resulting from the technology projections and trends with the assembled information on the type and distribution of referenced literature with respect to subsection categories as originally defined in Task 2. The status of each item could then be designated as follows:

V = Void. A significant knowledge or technology void exists that will not be overcome without further research and/or development. This code has been used where either a general knowledge void exists or where there has been no apparent attempt to focus and apply general knowledge to situations/environments peculiar to space teleoperations.

I = Insufficient. Though some literature pertinent to this issue has been cataloged, what is available does not appear to be sufficient to resolve open questions. The two principal reasons for assignment of this code were: the issue was considered only indirectly in the literature; and findings or recommendations of research do not appear to have yet been adequately validated.

I/A = Adequacy Suspected. This category exists because study team resources have proven to be insufficient to obtain the needed analytic depth. Issues assigned this code were those for which only a few citations were catalogued, yet the study team's experience indicated adequate literature should be available to make the subject a "non-issue." A focused, in-depth analysis is necessary to determine if adequate information exists to resolve the questions (issues) that have been identified.

A = Adequate. Available literature for this subject makes it a "non-issue" that will warrant research only if some situation specific perturbation is uncovered.

The information voids are identified and tabulated in the Task 4 report. However, this data is further integrated and characterized into a minimum, but sufficent set of analyses, experiments, and tests in task 5. Because Task 5, generation of the Human Factors Research Plan, is the ultimate objective of the first five tasks in this study, it would be irrelevant to include that data set herein. Refer to Section 5.0, Task 5.

5.0 TASK 5 - HUMAN FACTORS RESEARCH PLAN (HFRP)

5.1 OBJECTIVE

The objective of this task was to define and characterize the tests, experiments, and analyses necessary to provide the missing elements of data/knowledge for each item from the composite list of Task 2. Further, by exploiting commonalities, a minimum but sufficient set of tests, experiments, and analyses that provides the required data was defined and described. Special constraints, such as testing requiring a zero-g environment or a particular order or sequence, were included in the definitions. The results of this task were documented in the "Human Factors Research Plan". Refer to MCR 84-512, Task 5, for a detailed description of the plan.

5.2 APPROACH

The major parts of this research plan are summarized in Figure 5-1, which shows the general task flow. About 100 missing issues of data/knowledge resulting from the composite issues list were characterized, screened, and integrated into a minimum, but sufficient verification set of tests, experiments, and analyses. The integration also considered the areas of human interactions required or projected based on general task objectives and complexities.

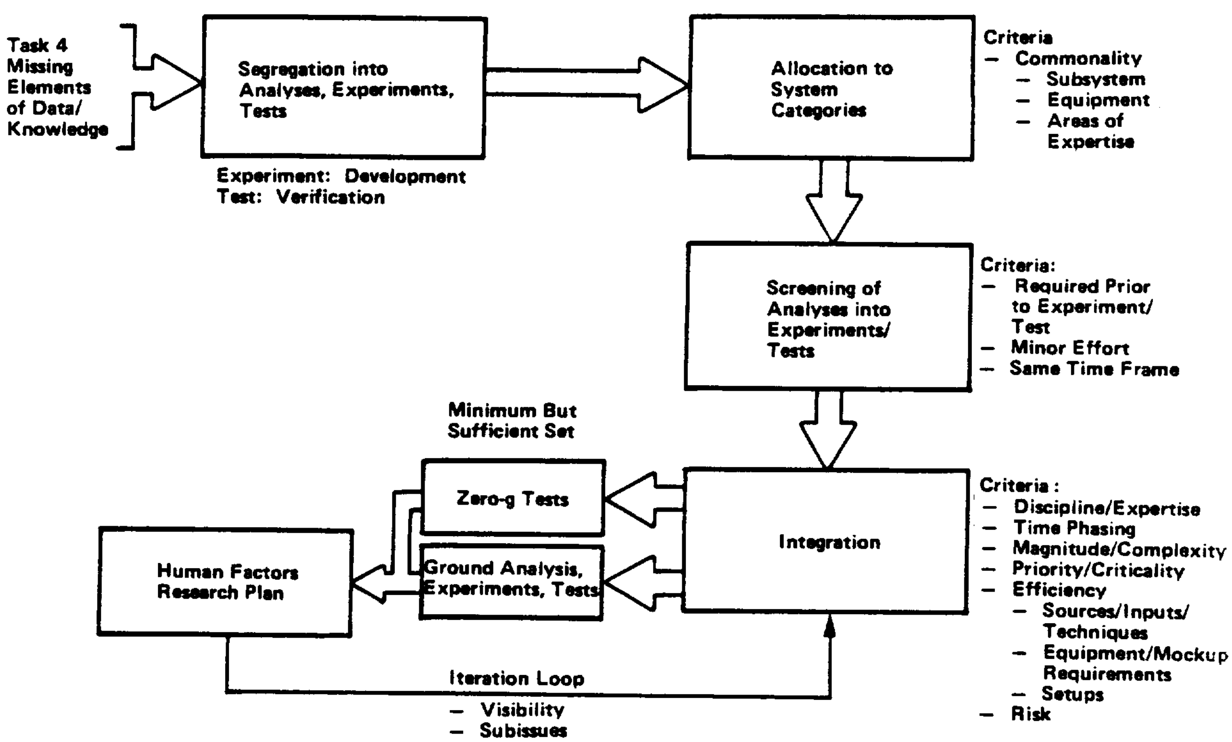


Figure 5-1 HFRP Approach Flow

5.2.1 Integration Process

The composite list of issues from Task 2, as modified by data determined to be available in Task 4, was first segregated into analyses, experiments, and tests (see Fig. 5-1). They were then allocated to their respective system categories, such as human operator, control station, communications, and space system, and segregated into common elements within those categories. Analyses integrally related to specific tests and experiments were then combined (screened) with those so identified. Based on the criteria shown in Figure 5-1, the final integration process further combined individual analyses, experiments, and tests into the required minimum but sufficient set.

No zero-g test or experiment requirements were identified. The iteration loop shown allows reassignments as necessary as greater visibility is provided during the generation of the individual test plans.

5.2.2 Time Phasing

With a representative spectrum of space teleoperation activities established as a focus, issues having data voids were prioritized and sorted into time phases. The first includes those issues in which the data voids were considered to be critical to near-term development and enhancement of a teleoperation system. The later phase is related to those issues in which the data voids were considered to be longer term research and technology development issues where favorable results could substantially advance the teleoperations capabilities in the areas of performance growth and higher levels of supervisory control.

The near-term areas included human performance and man-machine interface, communication and computational system architecture, sensors, hardware requirements, control modes, stability and trajectory optimization, task simulation, and shared manual/computer control.

The longer range opportunity areas identified included supervisory control, user-friendly interfaces, robotic system architecture, coordination of multiple processes, sensor-based adaptive control, scene understanding, control of flexible or "limber" manipulators, fine and dexterous manipulation, goal-oriented automated planning, expert system monitoring, fault detection, isolation, and methods for recovery.

In summary, the research needed to establish human performance capabilities and man-machine interfaces for control of teleoperators is reflected in this plan. The objectives are to determine human capabilities and limitations in teleoperation; to develop design guidelines for teleoperator procedures, testing, and control stations; and to develop techniques to provide enhanced sensory feedback to human operators.

5.3 RESULTS

5.3.1 Integration

The integrated analyses, experiments, and tests are shown in Tables 5-1, 5-2, and 5-3 respectively. The number identifiers are maintained for consistency with the individual task reports. Refer to the Appendix or the referenced Task 5 report for a detailed description of each item. Additional data is contained in the "Remarks" column. The "Integrates" column refers to the original items from the composite listing.

The category ("Cat") column lists the recommended timeframes for performing the activities as early, medium, or late (E, M, or L) and the priority (criticality) or importance as 1, 2, or 3 with "1" being the most important, indicating that other issues or mission success are dependent on the resolution. Medium criticality indicates the issue is important, but resolution is not a determinate for other issues. Low designations have obvious human impact, but lack of resolution will not precipitate mission failure.

5.3.2 Time Phasing

The recommended activity performance time phasing is shown in Figures 5-2 and 5-3 for the integrated analyses, experiments, and tests. Where applicable, interactions between the different activities are indicated. Note that abbreviated titles are used for the activities to simplify the figures.

Table 5-1 Integrated Analyses

Analysis No.	Title	Integrates Analyses/or Previous No.	Cat	Remarks
101	Information Processing Models	5	M3	
102	Human Performance Characterization	6,7,44,45	M2	
103	Operator Pool Definition	9	E1	
104	System Life Span Impact	64	L2	
105	Human Model Development	3	E3	
106	Work/Task Analysis	11,12,13	E1	Long-term, Iterative
107	Control Station Architectural & Ergonomic Considerations	14,15,19	M2	
108	Equipment Qualification Testing	16	M2	
109	Display Hardware Alternatives Assessment	17	M2	
110	Processing Operations Policies & Administrative Modules	22,23	E1	
111	Hardware Selection Criteria	24,25	M2	
112	Software Selection Criteria	26,27	M2	
113	Ground/Space H/W & S/W Allocation Methodology	28,40	E1	
114	Ground/Space Allocation Cost Model	29,51	M1	
115	Degree of Autonomy Feasibility	30,31	M2	
116	Real-Time Data Adequacy	32	M1	
117	Time-Delay Alternatives Assessment	33	E1	After Test 104
118	Mechanism Structure & Characteristics	35,36	M1	

Table 5-1 (concl)

119	Sensory Perception Devices	37,38	E1	Large Effort, Perhaps Late Test
120	Autonomous Position & Orientation Sensing Techniques	39	E2	Difficult
121	Autonomous Versus Teleoperation Task Assignments	41	E1	
122	Rqmts for Autonomous & Teleoperated Operations	42,43	M1	
123	Teleoperation Testing Rqmts	46	L1	
124	Teleoperation Versus Alternate Approaches Testing Levels	47	E2	
125	Material & Module Transfer I/Fs	49	M2	Test 18, L2
126	Servicing Mechanical I/F Capabilities	50,52	E1	
127	Servicing Rqmts & Design Guidelines	53,54,55	M1	Related to Test 110, L1
128	Host Spacecraft Design Considerations for Servicing Missions	56,57,58	M2	
129	Remote Task General Dimensions & Structure	59,60	M1	
130	Task Panel Definition & Usage	61,62	E1	
131	User Compatibility Rqmts Planning	63,66	M1	
132	Technology Development & Maintenance Support Planning	65,68	M2	
133	Fault Tolerant System Trade Analysis	67	M2	

Table 5-2 Integrated Experiments

Exp. No.	Title	Integrates Analyses/Exp No.	Cat	Remarks
101	Establishment of Human Perceptual Capabilities & Limitations	Exp 1	E2	Early, Rough Control Station
102	Determination of Human Cognitive Styles, Performance Factors, & Selection Criteria	Exp 3 Anal 8,10	L1	Same as 101
103	Early Assessment of Operator's Display Information	Exp 4,5	E1	Two Parts: E1, Same as 101; M1, See 104
104	Late Assessment of Operator's Display Information	Exp 4,5	M1	High-Fidelity Station
105	Applicability of Computer-Aided Input Control Devices	Exp 6	M2	

Table 5-3 Integrated Tests

Test No.	Title	Integrates Analy/Epx/Test No.	Cat	Remarks
101	Operator Characterization for Optimal Control Station Design	Test 1 Anal 1,2	E2	Early, Rough Control Station
102	Design Constraints Related to Human Information Limitations & Presentation Techniques	Test 2, Exp 2 Anal 4,20,21	E1	Same as 101
103	Controls/Displays Design Parameters	Tests 3,4,5 Anal 18	M1	
104	Time Delay Effects	Test 6 Anal 34	E1	
105	Video Bandwidth Rqmts	Test 7	M1	
106	Module Attachment Techniques	Test 8	E1	Non-op, Early Mock-up
107	Mobility Design Parameters	Tests 9,11	M2	Late, Full Mock-up
108	Teleoperation Rqmts & Design Guidelines	Test 10 Anal 48	M1	
109	Scene Illumination Rqmts & Motion Effects	Tests 12,13, 14 (Vision)	M1	
110	Attachment During Servicing, Component Replacement, & Motion Effects	Tests 14 (Manip), 15,16	L1	Late Mock-up
111	Task Element Structure	Test 17	--	Integrate Into Other Applic-able Tests
112	Material Transfer Mechanical Interface Parameters	Test 18	L2	Full-Scale Mock-up of Worst Case

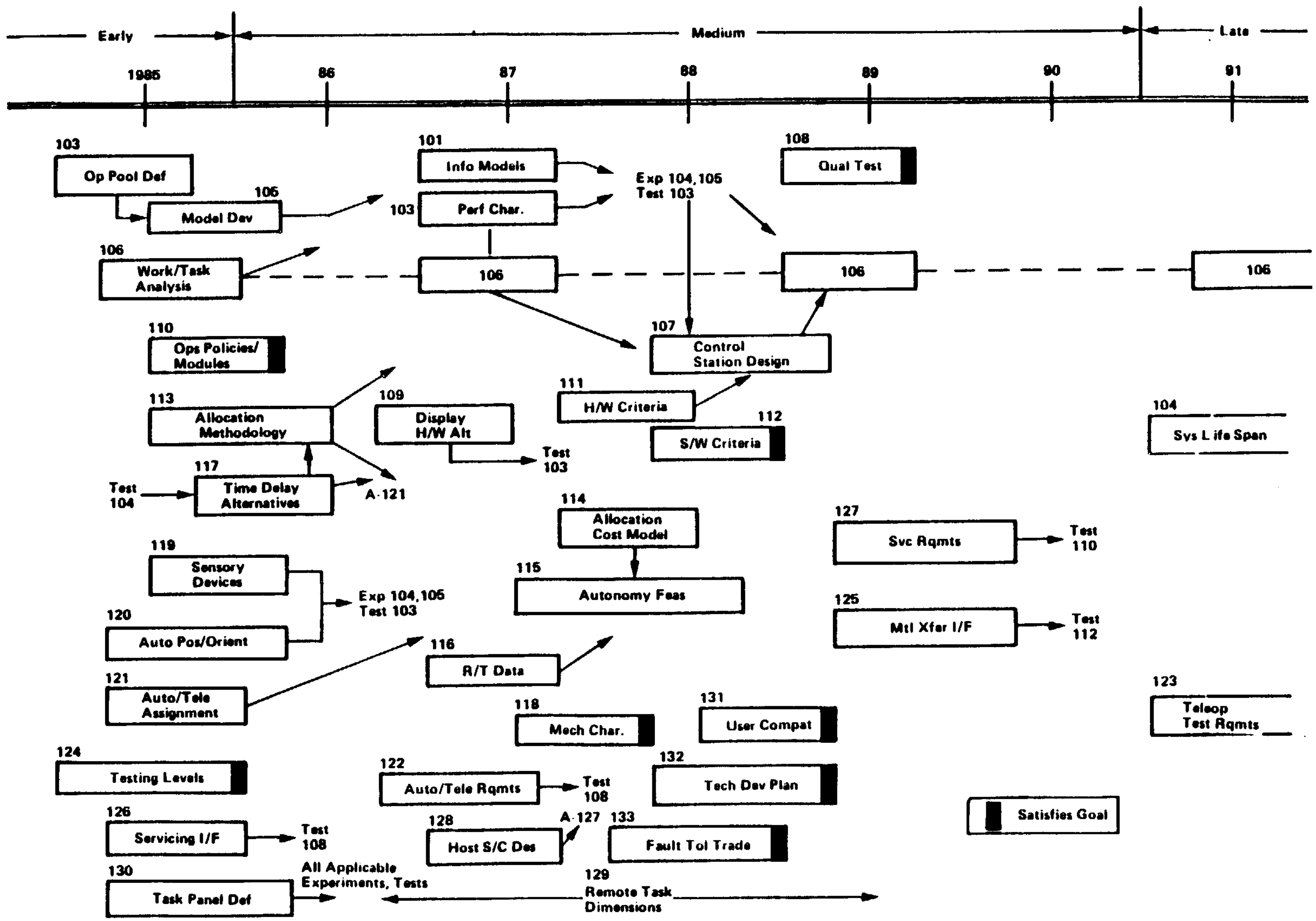


Figure 5-2 Integrated Analysis Time Phasing

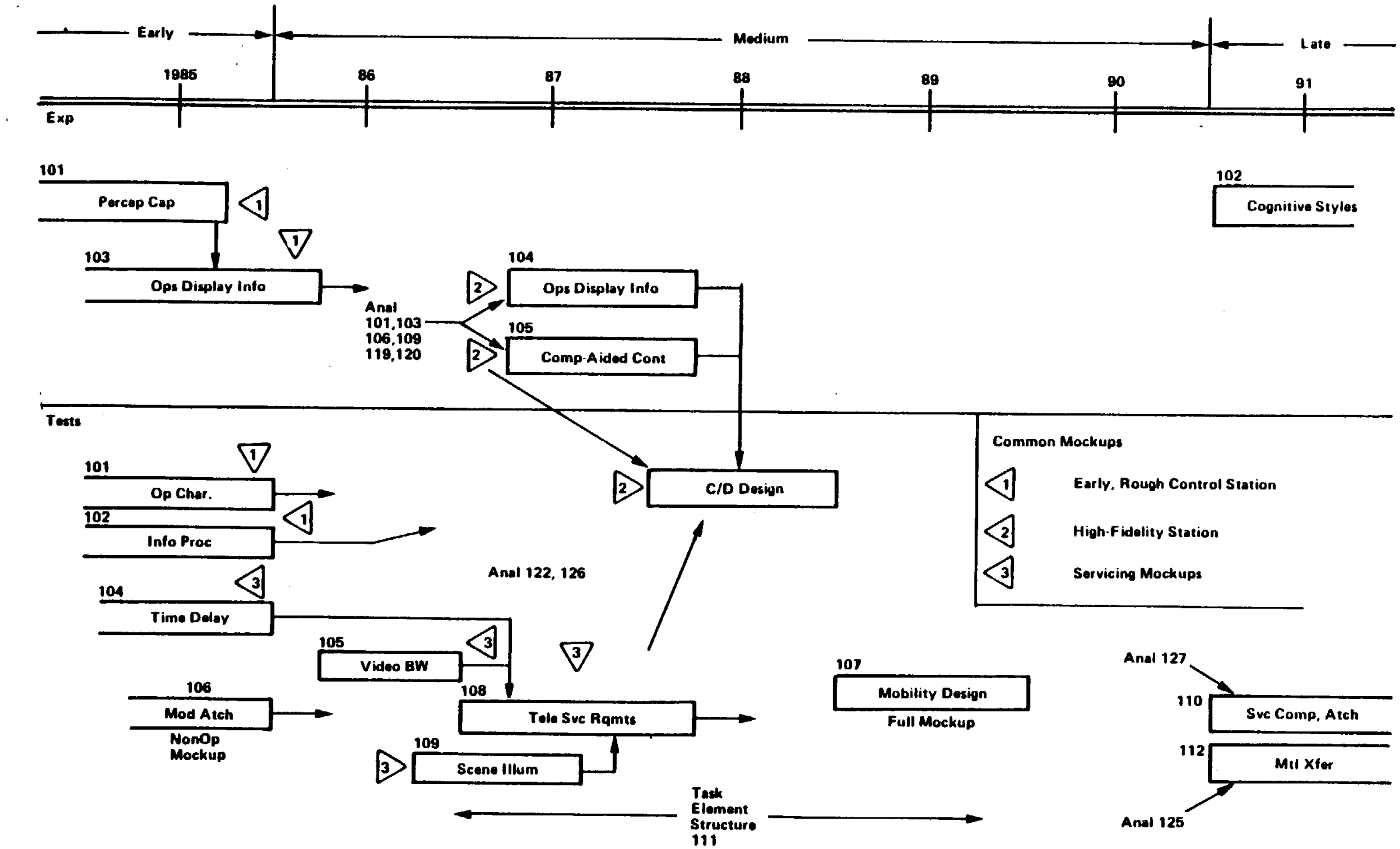


Figure 5-3 Integrated Experiments/Tests Time Phasing

6.0 TASK 6 - HUMAN FACTORS RESEARCH PLAN IMPLEMENTATION

6.1 OBJECTIVE

The objective of Task 6, as specified in the statement of work, originally was to define and document facility requirements for accomplishing the individual elements of the Teleoperator Human Factors Research Plan as defined in Task 5. However, it was found that data describing the capabilities of various NASA and other facilities already existed. The utility of a description between the specified test facility requirements and the existing facility capabilities was questionable, because in many cases the tests could be redefined or performed in different ways. Thus, the final facility assessment was believed to be best left to those agencies interested in performing the individual tests.

A useful and practical approach was to actually perform a limited set of tests. Thus, the facilities definition was deemphasized and the effort focused on performing testing in the MSFC robotics laboratory.

The testing specified in the revised statement of work contained a limited set of tests from the Teleoperator Human Factors Research Plan (Task 5), including:

- Assessment of the force-torque end-effector,
- Minimum video operation,
- Stereo viewing assessment.

The performance of the three items above was predicated on the delivery of an end-effector from JPL and a new stereo system. However, these expected deliveries did not occur. Therefore, the specific tests and activities performed were as follows, and are encompassed within the intent of the statement of work.

1) Operator Selection,
2) Baseline Task Definition,
3) Control Mode Study,
4) Lighting Study,
5) Camera Study,
6) Preliminary Time Delay Study.

Data derived from these tests and activities are summarized herein, along with the approach used and some general conclusions. For details concerning these data, refer to the Task 6 report, MCR 86-558.

6.2 APPROACH

The general approach to the overall task performance regarding specific methods relevant to the individual activities are included in Section 6.3.

Before test implementation, it was obviously necessary to first define a pool of operators through a selection process. To measure each subject's performance under various test conditions, a baseline task was defined. This task used the Proto-Flight Manipulator Assembly (PFMA), a remote operator's station with video displays, a CAE six degree-of-freedom hand controller, and a task panel for manipulations with the PFMA. Video data was provided by a camera lens on the wrist of the PFMA, coupled to the camera electronics via a fiber optics cable, with peripheral cameras, and lights.

To make optimum use of the available resources, a set of guidelines and groundrules were established before beginning the operator selection process and test performance.

1) Study Thrust--Treat operator as simply a major system element and not concentrate on the selection criteria, training, etc.

2) Operator Selection--How does the operator perform with the PFMA system. Do not stress such criteria as what is the optimum category for selection of candidates.

3) Results--Obtain meaningful results, rather than theoretical, and keep output data simple and meaningful.

6.3 RESULTS

6.3.1 Operator Selection

6.3.1.1 Introduction--To create the subject operator pool, a list of volunteers from within MSFC was solicited. This list was then reduced to a pool of five or six individuals best-suited for teleoperation activity. But how to determine which individuals are best-suited for this kind of activity? We began by making some assumptions about the characteristics of individuals that could be related to good teleoperation performance. We assumed that skilled manipulator operators would have good spatial abilities, above average intelligence, and interests and education similar to astronauts and mission specialists.

To gather this information about our subjects, we administered several psychological tests and a questionnaire. We used two subtests of the Differential Aptitude Test (DAT)--the Space Relations subtest and the Abstract Reasoning subtest--plus the Raven Progressive Matrices Test, which measures intelligence nonverbally. The questionnaire assessed general interests, academic background, and past experience related to teleoperation.

6.3.1.2 Method--The experiment was executed in two parts: first, individual performance on a simple manipulator task (a peg-in-the-hole task) was collected, and then the psychological tests and the questionnaire were administered. Performance data was then correlated with the test scores and questionnaire responses and a selection instrument devised. A total of seventeen individuals completed the study.

During the 30-minute session spent controlling the PFMA, each subject completed four repetitions of the peg-in-the-hole task. While each subject worked through the task, two response times were noted: (1) Time 1: the time needed to move the arm from the starting position to a point where it was possible to grip the peg and remove it from the hole, and (2) Time 2: beginning at the starting position, the total time needed to insert the peg in an opposite hole. The test setup is shown in Figure 6-1.

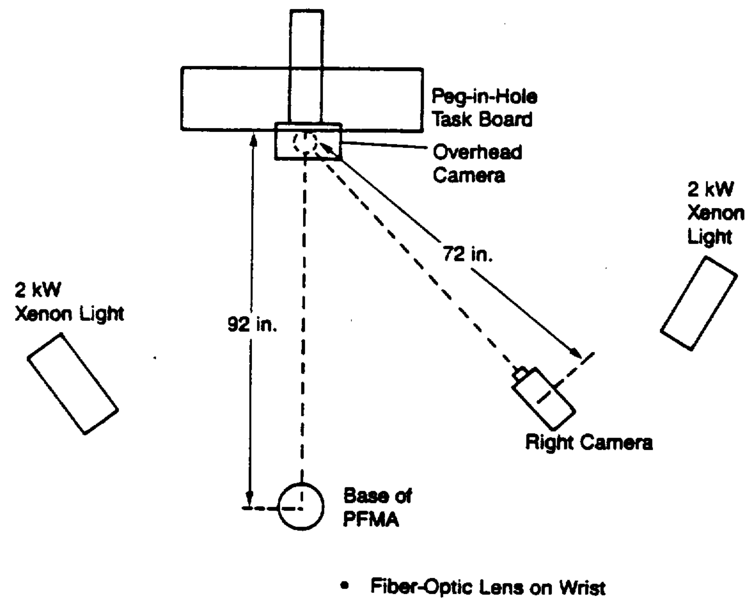


Figure 6-1 PFMA Test Bed Setup

6.3.1.3 Results--To compare subjects, the last three trials were averaged together for each of the task times. These averages were then used to rank each subject. By considering each subject's errors, as well as their ranks on the task scores, it was possible to get a qualitative assessment of each subject's performance.

After completing all four experimental trials, each subject completed the Cooper-Harper Scale before completing the questionnaire. The average Cooper-Harper score, which is designed to assess subjective mental workload, indicated that most subjects felt the task was fair and mildly difficult. Additionally, the task was perceived as requiring acceptable operator mental effort to attain adequate performance. Following completion of the experimental trials, the subjects completed a 16-item questionnaire that assessed past experience, level of education, interests, and general comments about the experiment.

6.3.1.4 Selection Instrument--Using the test scores, questionnaire data, and the performance scores, we devised a method for downselecting our subject pool from our original 17 volunteers. Five composite scores were created from the questionnaire items: related experience, academic achievement, years in present profession, interest in computers, and video game experience. By correlating task performance times with the three test scores and these five composite scores, we hoped to find which of these measures correlated with performance and would therefore be a predictor of manipulator ability. The eight predictors were then entered into a stepwise regression equation to determine which scores successfully predicted task performance. The regression revealed the only variable that was relative to task performance was the video game score. Eight subjects were then chosen for further testing, based on task performance. They were evenly divided among high and low related experience factors.

6.3.1.5 Conclusions--The results of the operator selection experiment revealed that the aptitude tests and questionnaire responses were not useful predictors of manipulation abilities. Even though the peg-in-the-hole task provided a wide range of performance times, and subjects demonstrated a range of operational styles, the test scores and questionaire responses were not sensitive to these performance differences. However, because individual differences in operational style were readily observed, there is still hope that a personality test might prove useful as a selection instrument for manipulator operators.

6.3.2 Definition of Baseline Task

Again, to meet the goal of obtaining meaningful results, an operational task other than the peg-in-the-hole task was required. Therefore, a new task was devised that was relatively complex, somewhat realistic from an operational standpoint, brief, and required a range of manipulative abilities. This task was called the "baseline task", because performance on this task would provide a measure of each subject's baseline performance with the PFMA. Then, once a baseline was established for each subject, it would be possible to experimentally compare their baseline performance with future performance on the same task with less-than-optimal arrangements of camera views, light intensities, and time delays, etc.

Baseline performance was assessed under what was determined to be an optimal configuration of the apparatus in the lab. This consisted of:

1) Three camera views: one directly over the task board, one at a 45-degree angle to the board, and a "bird's eye" fiber optic view mounted above the wrist joint;

2) Optimal lighting;

3) Monocular video (this may or may be optimal, but a workable stereo system was not available for evaluation);

4) No time delay.

As mentioned previously, the baseline is much more complicated than the peg-in-the-hole task used for operator selection. The baseline task, developed with a task board and equipment available at MSFC, actually consists of nine subtasks that can be timed separately by the experimenter. Table 6-1 describes these subtasks, and the control motions required to perform them.

Table 6-1 Subtasks of Baseline Task

Baseline Subtasks		
SUBTASK #	DESCRIPTION	MOVEMENTS REQUIRED
1	Move from the starting position to the task board and grasp the door handle of the compartment.	X, Y, and Z translations, as well as pitch and roll movements. In addition, the grippers had to opened and closed.
2	Open the door a few inches, and then release the handle and push or bump the door to a fully opened position.	X, Y, and Z translations and yaw movements.
3	Grasp the handle of the module.	X, Y, and Z translations and some pitch and yaw movements.
4	Pull the module from the compartment.	-X and some Y or yaw movements were required; as well as some pitch movements.
5	Once extracted, the module had to placed inside a 14" X 14" x 2" high cardboard box on the floor.	All six degrees of motion were required.
6	After dropping the module in the box, the subject was required to touch a piece of tape with the end effector. The tape was placed over the compartment.	All six degrees of motion were required.
7	After touching the tape return to the module and grasp the handle.	All six degrees of motion were required.
8	Reinsert the module in the compartment.	All six degrees of motion were required.
9	Close the door of the compartment.	X and Y translations and yaw movements.

6.3.3 Control Mode Experiment

6.3.3.1 Introduction--The PFMA has been programmed to run under three distinct operational modes: terminal mode (a wrist-referenced mode), hawk mode (a shoulder-referenced mode), and a joint-by-joint control mode. An experiment was undertaken to compare performance on the baseline task using two of the three modes, the terminal mode and hawk mode. Because many researchers have found that resolved rate modes are better than joint-by-joint modes, we chose to evaluate only the hawk and terminal modes.

Commands issued in hawk mode move the arm and end-effector with respect to a fixed coordinate system, roughly defined by the grid of the floor tiles in the lab. In terminal mode, the operators' coordinate system for moving the arm is defined by the wrist of the PFMA (the direction the end-effector is pointing). In addition, because the fiber-optics camera is mounted above the wrist, a straightforward direction is also indicated by the view of the camera.

6.3.3.2 Method--Ten of our original pool of seventeen subjects completed this evaluation. The eight subjects "chosen" for the subject pool completed this study, along with two additional subjects that were available. The subjects completed at least two trials with each mode.

Data for each subject consisted of the time (in seconds) required to complete each of the nine subtasks, as well as the total task time, and a Cooper-Harper rating for each trial. Each of these subtasks times was then averaged together across operating modes to create average subtask times for hawk and terminal modes.

6.3.3.3 Results--There was a significant difference between hawk and terminal modes for only one subtask, Subtask 8. As shown in Table 6-1, this subtask required the subjects to pick up the module and reinsert it in the compartment. For this task the terminal mode was much faster, an average of 102 seconds versus 200 seconds for hawk mode. This indicates that for the complicated task of picking up a module, aligning it with a compartment, and inserting it, the terminal mode was much easier. Even though Subtask 8 was the only one showing a significant difference between operating modes, terminal mode times were generally faster than hawk mode times for all but two subtasks. The Cooper-Harper ratings of the two modes were significantly different. Subjects rated the terminal mode trials easier than the hawk mode trials.

6.3.3.4 Conclusions--Control modes that use fixed coordinate systems (shoulder-referenced modes) may make certain types of manipulator operations more difficult. Hawk mode required the subjects to input tricky cross-couplings of +X and -Y commands in the hand controller. Terminal mode also has a few problems, but the subjects seemed to adapt to the intricacies of this mode more quickly.

6.3.4 Final Subject Pool

Based on the operator selection testing and performance on the baseline task during the control mode study, a final set of six subjects was selected to comprise the subject pool. During the baseline testing, we quickly learned that operator speed was a poor criteria for choosing subjects for future research. Some of the subjects who performed the task the quickest were also difficult to schedule, impatient with the task, and often uncooperative. Therefore, other subject variables were considered in our final decision. These included availability, attitude, and to a lesser extent, performance. Based on these criteria, four males and two females were selected to comprise our subject pool.

6.3.5 Lighting Study

6.3.5.1 Introduction--Using the baseline task, operator performance with varying light levels at the worksite was examined. The apparatus setup was slightly different for this study. Because of the difficulty of implementing an overhead camera for space operations, the overhead view used in earlier baseline testing was removed from the operators' console for realistic test conditions.

To control the amount of light reaching the task board, the overhead lights in the lab were extinguished and a black cloth was placed on the floor beneath the task board to eliminate reflection off the floor of the adjustable xenon lamps. Four levels of lighting were examined: high, medium, low, and a shadow condition. Foot/candle intensity readings were taken for each of the light conditions through the use of a light meter aimed at the task board. The readings taken were as follows:

High	2.5 foot/candles or 250 lux
Medium	1.0 foot/candles or 100 lux
Low	0.6 foot/candles or 60 lux
Shadow	0.8 foot/candles or 80 lux (one light off, other on medium)

6.3.5.2 Method--The subjects used for this test were four members of our subject pool. With the remaining two camera views--the 45-degree angle camera and the fiber-optic camera--each of our four operators completed five repetitions of the task under different lighting conditions.

Subjects completed one warmup trial under high-intensity lighting, and then completed a second high-intensity trial followed by three additional trials under the other lighting conditions. The order of the trials was counterbalanced, after the subject completed the warmup trial.

6.3.5.3 Results--The repeated measures analysis of variance (ANOVA) revealed no significant differences as a result of lighting levels, $F(1,3) = 0.29$, $p < .825$. The results of multiple analyses of variance profiles also supported this finding.

6.3.5.4 Conclusions--A technical problem may have contributed greatly to our negative finding. Because the setting for the automatic iris of the fiber optics camera was "on", operators received good quality video output from that camera for all lighting conditions. Because the picture provided by the fiber optic camera was not affected by changes in lighting levels, operators were able to rely more on that view to complete the task.

It seems logical that an automatic iris setting for cameras at the work site would be advantageous, but studies at Martin Marietta on OMV docking simulations revealed that pilots prefer a manual override to the automatic iris. During these simulations, the automatic iris would often adjust itself to light reflecting off the body of the satellite or the solar panel, leaving the pilot with a dim view of the docking probe.

6.3.6 Camera Study

6.3.6.1 Introduction--Using experimental trials from the control mode study and similar trials from the lighting study, it was possible to do a post hoc analysis of the effect of a third camera view of the work site.

6.3.6.2 Method--Four subjects from our pool completed similar trial runs of the baseline task with and without an overhead camera.

6.3.6.3 Results--A repeated measures analysis of variance revealed there were no significant differences on task performance related to camera views for total task time. However, for Subtask 3, a significant difference was observed, whereby, the overhead camera view facilitated the gripping of the module's handle when it was in the compartment. Because the overhead camera was only advantageous for Subtask 3, a two-camera setup was used for the later studies. These results agree with other studies that found when operators were allowed to change camera views of a computer graphics representation of a manipulator arm and task board, they preferred two orthogonal views. View 1 was roughly at a side view of the task board and slightly above center with a 60-degree field of view. View 2 was positioned above the center of the board looking down at a 70-degree angle.

6.3.6.4 Conclusions--The use of a third camera for an overhead view does not seem necessary for further research with the baseline task because it would be difficult to achieve in an operational setting, and the subjects performed well without it.

6.3.7 Preliminary Time Delay Study

6.3.7.1 Introduction--Time delays are an unavoidable consequence of sending transmissions to and from space-based vehicles. Because these delays may range anywhere from .5 to 8 seconds, depending on the number of satellites the signal must pass through and data processing times, operators of space-based manipulators will have to contend with these delays as they perform complex teleoperations. The question is how to best design the teleoperator system interface to limit the harmful effects of these delays.

Because it is obvious from other studies that time delays directly affect task times, we intended to concentrate our efforts on how the baseline task is performed, not the speed. We anticipate that delays will affect operator performance in a number of ways.

To begin to answer some of these questions, additions to the PFMA software at MSFC were required. The data collected by these subroutines consists of:

1) Total time from start to finish of each trial,

2) Total number of distinct hand-controller inputs,

3) Total duration of translational inputs,

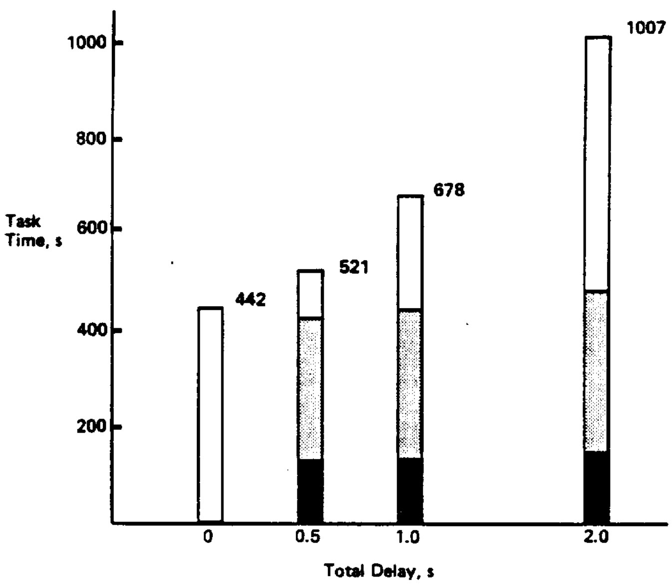
4) Total duration of rotational inputs.

With this data we were able to compute the total amount of time the PFMA was actually moving (duration of translations plus duration of rotations). Knowing this, it was possible to determine the amount of time the arm was not in motion (this amount of time reflects the time spent by the subject thinking about what to do next, as well as waiting for the delays).

6.3.7.2 Method--Subjects for this experiment consisted of five individuals from our pool. However, only three subjects were able to complete trials under all delay conditions. Four levels of time delay were used in this preliminary study: no delay, 0.5-second delay, 1-second delay, and 2-second delay. This delay was achieved by modifying the software so that commands from the hand controller were delayed x amount of time before being executed by the arm.

The subjects began the experiment by completing one warmup trial (no time delay was used). Following this trial they completed as many delay trials as they could in the time that remained in the two-hour sessions. The presentation of time delay trials was counterbalanced across subjects.

6.3.7.3 Results--Rotational, translational, and total data for the three subjects was averaged across delay conditions and presented in Figure 6-2. Individual trial data was analyzed via repeated measures analysis of variance and profile analysis. As would be expected, the level of time delay significantly affected task times. The results of the profile analysis are presented in Figure 6-3.



	Time Delay			
Times	0	0.5	1.0	2.0
Rotation Duration	–	123	129	145
Trans Duration	–	296	317	337
Thinking/ Waiting	–	102	232	525
Total	442	521	678	1007

Figure 6-2 Time Delay Data

As in earlier studies, minor errors were expected to affect task times, but because it is unreasonable to expect operators to perform the task perfectly every time, minor mistakes were generally ignored and the subjects allowed to continue without interruption. Major errors, on the other hand, can drastically affect performance, so they were noted on the data sheet, but were not analyzed because they were infrequent.

6.3.7.4 Conclusions--The results of the profile analysis simply confirms an obvious result: Increased time delays cause an increase in task performance times. More interestingly, the data displayed in Figure 6-2 indicate that even though task time was increasing as delay increased, duration of hand-controller inputs for translational and rotational commands did not increase. Therefore, operators were not forced to input more hand-controller command when working witn time delays.

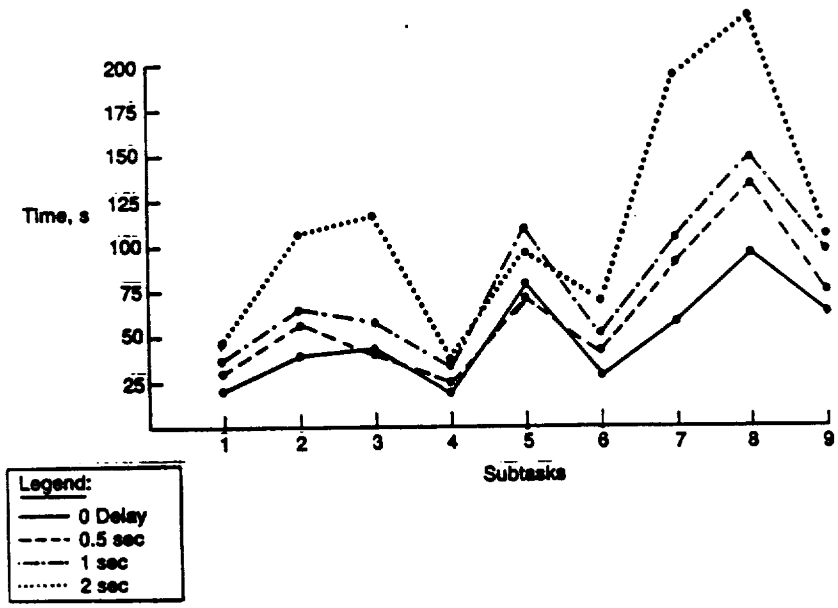


Figure 6-3 Profile Analysis–Time Delay Study

Also, the subjects did not always move-and-wait as was generally expected. Our subjects, being extremely familiar with the task, put multiple moves together before finally waiting to see the results of their actions. This was especially true with 0.5 second delay. However, when the delay was 2 seconds they spent more time waiting, but did not wait for every move. One finding that was consistently observed, but is not presented in the data, is that with longer delays subjects spent more time waiting for feedback during Subtasks 3, 5, 7, and 8. (These subtasks are the ones that require the operator to be extremely precise with movements).

Surprisingly, the operators that completed the task with all of the delay conditions expressed the opinion that the delays didn't really cause much difficulty. Their task times and their Cooper-Harper scores supported their comments. As a reminder, the operators were provided with two camera views of the task board providing television-quality video. When we combine time delays with limited bandwidths, along with increasing delay times, the true effect of time delays on space-based teleoperation will become apparent.

6.4 TASK 6 GENERAL CONCLUSIONS

6.4.1 Operator Selection

The THFS has provided some very interesting conclusions. The use of aptitude tests and questionnaire items to assess individual characteristics of our operator pool was not useful in selecting "good" operators. Test scores, related experience, and general interests did not correlate with task performance, but video game experience did.

6.4.2 Operation of PFMA

Use of the six degree-of-freedom (DOF) CAE hand controller had some advantages and disadvantages. It afforded an operator the opportunity to control a six-DOF arm with only one hand, which will be critical if dual-arm manipulators are used. In addition, it allowed an operator to input moves in multiple axes at one time, but unwanted cross-couplings also occurred. Operators often coupled translational and rotational movements together when trying to execute pure translational commands. In light of these findings, we recommend not abandoning use of separate rotational and translational hand controllers.

The correct manipulator control mode is critical to successful teleoperations. As demonstrated in our study, our operators were able to use both modes effectively, but the wrist-referenced mode was easier to use for most operations.

6.4.3 Cameras and Lighting

From a post hoc analysis of camera views, it was concluded that three views of the task board were unnecessary. A fiber-optic lens mounted above the wrist and connected to a video camera providing a "birds-eye-view" of the scene, and a camera mounted at a 45-degree angle to the task board were adequate for the baseline task.

Through the lighting study it was determined that operators could successfully perform the baseline task with a poor quality picture from the 45-degree angle camera as long as they were given a good picture from the fiber-optics camera.

6.4.4 Time Delays

Time delays did not cause operators as much difficulty as we initially thought they might. It should be noted that trials were conducted with television-quality video. If operators performed the same trials with longer delays, limited picture resolution, slower frame rates, and reduced grey levels, it is unlikely that the time delays would continue to have such a minimal effect on task performance.

6.4.5 Rate of Manipulator Travel

The rate of travel of the manipulator arm is important to good operations, but it hasn't been systematically studied. Anecdotal evidence indicates that "hot" arms are extremely difficult to control, especially when working with time delays. Likewise, controlling arms with very slow rates is also not advised because performing many long translations would become tiresome for the operator.

The rate of the PFMA translations at the end-effector tip was approximately 2 ft/s (maximum extension). Operators seemed to work well with this rate. Rotational rates were a little slower, but this is probably advisable when working close proximity operations. Research on different rates should be done to determine the correct balance between speed and precision.

6.4.6 Learning Effects

An examination was made of the suggestive work load assessments (Cooper-Harper ratings) as a function of learning, i.e., operator experience with the system, as testing progressed from the study beginning through the last tests. It was found the data could not be realistically correlated because of the wide fluctuation in experimental conditions where new variables were being injected.

6.5 FUTURE RESEARCH

During the course of this study it has become obvious there are many areas of teleoperator research that have not been adequately studied. Some of these are: selection of operators, use of stereo- vision systems with space-based manipulators, working with limited bandwidths, use of force-sensing hand controllers, and the effect of time delays on complex task performance. Each of these areas has been studied singularly, but research examining interactions of variables has not been done except in a few instances. Refer to the Task 6 report, MCR 86-558, for an expansion of these and other areas.

APPENDIX

INTEGRATED ANALYSES, EXPERIMENTS, AND TESTS

HUMAN FACTORS RESEARCH PLAN

INTEGRATED ANALYSES

<u>Analysis 101 - Information Processing Models</u>

Develop applicable information processing theories/models to ultimately establish intelligent automation or to provide computer models of the human operator for system testing.

- Information processing (assimilation rates/capacities)
- Memory
    - Long term
    - Short term
    - Facts versus skills
- Reaction times
- Feedback time delays

<u>Analysis 102 - Human performance Characterization</u>

Quantitatively establish the human performance capabilities, interactions and physical/mental effects as follows:

a) The perceptual-motor capabilities (optimal performance ranges and constraints/limitations) and physical/mental effects of the human operator in the performance of the teleoperator manipulation and mobility tasks.
    - Sensitivity
    - Dexterity
    - Reaction time
    - Tracking

b) Human interactions and effects in terms of the dynamics required in controls manipulations for adequate control station design.
    - Body movement
    - Dynamic forces
    - Static forces
    - Human constraints

<u>Analysis 103 - Operator Pool Definition</u>

Define the operator pool early and in terms of characteristics predictive of performance on teleoperator task in order to develop equipment and procedures commensurate with the abilities and weaknesses of the ultimate operating personnel.

<u>Analysis 104 - System Life Span Impact</u>

Determine a realistic operational system life span and assess the impact upon human factors issues.

<u>Analysis 105 - Human Model Development</u>

Develop human model for use in developmental testing.

HUMAN FACTORS RESEARCH PLAN

Analysis 106 - Work/Task Analysis

a) Allocate functions to man, man assisted by automation, or automation supervised by man.
   - Develop criteria
   - Determine implications for support equipment

b) Assess Operator Roles
   - Conduct task analysis
   - Conduct link analysis
   - Consider available skill pool
   - Consider capabilities of equipment
   - Conduct trade-off analysis

c) Determine Number of Operators
   - Consider operator role assessment
   - Consider timeline requirements
   - Consider operator physical limitations

Analysis 107 - Control Station Architectural and Ergonomic Considerations

a) Determine maximally effective layout of the control station to accommodate operator(s).

b) Design interfaces to accommodate 5th to 95th percentiles of the specialized population based upon data obtained in the characterization of the operator pool (anthropometry/biomechanics, perceptual capabilities).

c) Establish environmental considerations for control station design to determine if current design guidelines are adequate, particularly if the station is space-based.
   - Ambient lighting
   - Relative-humidity
   - Temperature
   - Air Composition

d) Evaluate alternatives in control station flexibility (functional and physical) to accommodate variable teleoperator task demands.
   - Reconfigurability
     - Element function
     - Element physical location
   - Portability
     - Ground-based location changes
     - Space-based station (Orbiter to Space Station)

Analysis 108 - Equipment Qualification Testing

Resolve testing issues related to the qualification of equipment for human use and evaluate cost/benefits tradeoffs.

Analysis 109 - Display Hardware Alternatives Assessment

Assess display hardware alternatives in terms of:
- State-of-the-art technology (and technology issues)
- Capability enhancement
- Operator acceptance
- Cost/benefits tradeoffs

Analysis 110 - Processing Operations Policies and Administrative Modules

a) Establish a set of policies that govern the integrated operation of all computing resources.
   - System architecture
   - Level of fault tolerance
   - Growth expandability
   - Cost effective system development and verification

b) Establish a set of management modules (hardware, software, firmware and documentation) that administers system policies.
   - Management policies
   - Teleoperation/automation interaction
   - Operator involvement

Analysis 111 - Hardware Selection Criteria

a) Establish a set of hardware selection criteria that meet program requirements at minimum cost.
   - Availability status
   - Importance and degree of fault tolerance
   - Maintainability
   - "User friendly" interfaces
   - Performance dependency (criticality)
   - Modular evolution capability

b) Investigate potential sequential developments with milestones for next 15 years.

Analysis 112 - Software Selection Criteria

a) Establish a set of software development and selection criteria that meets program requirements at minimum cost.
   - Available resources
   - Language choice
   - Database maintenance
   - Level of standardization
   - Functional allocations (partitioning)

b) Investigate sequential advanced software developments.

Analysis 113 - Ground/Space Hardware and Software Allocation Methodology

Establish methodology for allocating hardware/software elements to ground/space, including the effects of data errors and the necessity for error correction techniques and noise reduction.
- Task dependence
- Real-time computation/control
- Communications link availability
- Human operator (ground/space)

Analysis 114 - Ground/Space Allocation Cost Model

Establish if a limited cost model or life cycle cost model adequately predicts initial investment cash flow and program savings.
- Available cost models
- Alternative methods
- End-to-end functional description
- Qualification of alternatives
- Degree of autonomy tradeoff
  - Flexibility benefits
  - Criticality of data security
  - Standardization impacts

Analysis 115 - Degree of Autonomy Feasibility

a) Investigate the degree of autonomy available and feasible for incorporation into a teleoperation system.
   - Task dependence
   - Allocation of functions
   - Conventional/flexible automation
   - AI applications

b) Determine the decrease of ground personnel as a function of autonomy levels.

Analysis 116 - Real Time Data Adequacy

Determine if the projected real time communications capabilities can support the required level of direct human involvement.
- Levels of automation
- Task durations
- Downlink durations

Analysis 117 - Time Delay Alternatives Assessment

After the human performance and physical/mental effects caused by time delay have been quantitatively established by test, investigate alternatives to minimize the effects and tradeoff against the acceptability of the test results.
- NASCOM block-formatting
- Control station at White Sands
- Operator training
- Automation (space/ground)

Analysis 118 - Mechanism Structure and Characteristics

a) Establish optimum structure configuration for light weight and dexterous system.
   - New material trades
   - Envelope optimization

b) Determine manipulator characteristics that best satisfy task requirements and human involvement.
   - Compare manipulator module
   - Task complexity level
   - Performance capability
   - Anthropomorphism
   - Task duration
   - Next generation arm

Analysis 119 - Sensory Perception Devices

a) Determine what sensory information obtained by the teleoperator system at the work site is necessary or useful to the human operator in the performance of his tasks.
   - Vision systems
   - Speed
   - Force/torque

b) Determine what sensory information should be obtained at the work site for autonomous teleoperator operations, and what kind/type of this information should be available on demand by the human operator.
   - Interoceptive sensors
     - Temperature
     - Limits
     - Position
     - Speed
   - Extroceptive sensors
     - Temperature
     - Force
     - Touch
     - Proximity

Analysis 120 - Autonomous Position and Orientation Sensing Techniques

Determine adequate means of teleoperator systems sensing of its relative position and orientation in space, and detection/awareness of surrounding objects and the teleoperator system's relation, both static and dynamic, to those objects.

- Navigation systems
- Proximity sensors
- Laser ranging

Analysis 121 - Autonomous Versus Teleoperation Task Assignments

Determine a methodology for assigning tasks as autonomous or via teleoperation.

Analysis 122 - Requirements for Autonomous and Teleoperated Operations

a) Determine requirements relevant to both autonomous and teleoperated operations.
   - Hierarchical control
   - Multiple arm coordination
   - Adaptive control strategies

b) Determine requirements for autonomous servicing.
   - Processing requirements
   - Sensory integration
   - Onboard intelligence and decisionmaking

Analysis 123 - Teleoperation Testing Requirements

Establish level of verification testing required for teleoperator system.

Analysis 124 - Teleoperation Versus Alternate Approaches Testing Levels

Establish teleoperation testing levels as compared to testing required for alternate approaches.

Analysis 125 - Material and Module Transfer Interfaces

Establish the mechanical interface parameters needed to transfer materials/modules from spacecraft to teleoperator and vice versa.

- Degree of preparedness
- Transfer duration
- CG relation to grip points
- Optimum transfer paths

Analysis 126 - Servicing Mechanical Interface Capabilities

a) Establish mechanical interface capabilities and options on the host spacecraft that leads to an ever increasing level of servicing flexibility.
- Degree of S/C serviceability
- Time criticality
- Optimum flexibility (servicer/host)
- Access complexity
- Functional services adaptability

b) Establish degrees of design freedom for serviceable space systems resulting from projected technology innovations in servicer systems.

Analysis 127 - Servicing Requirements and Design Guidelines

a) Anchoring - Determine need for additional anchor arms/devices during servicing.
- Task sensitivity dependent
- Module add-on techniques

b) Degree of Structure - Establish work site serviceability design guidelines that support projected future remote service capabilities.
- Module access dependence
- Attachment alternates
- Space utilization trend
- Design verification through software
- Nonloaded connectors

c) Module/Component Interfaces - Investigate feasibility and acceptability of component replacement on orbit.
- Size dependence
- Accessibility to ORU
- Expert system contribution (CAD/CAM)
- Remote end-effector dexterity
- Contamination sensitivity

Analysis 128 - Host Spacecraft Design Considerations for Servicing Missions

a) Investigate feasibility of host spacecraft providing (or sharing) operating services to a teleoperator vehicle, i.e., power, communications link, station keeping, etc.

b) Investigate methods/techniques for providing system test or checkout and fault diagnostic host access ports for teleoperator vehicles.

c) Determine host spacecraft design conditions to address safety concerns or high risk.
   - Man-related
   - Mission related

Analysis 129 - Remote Task General Dimensions and Structure

a) Determine the dimensions of the tasks to be performed at the remote work site.
   - Task repetition
   - Task definition
   - Archival information requirements
   - Task timeline(s)
   - Task sensory requirements
   - Task dexterity requirements
   - Task complexity
   - Precision required
   - Engineering data requirements

b) Determine if conventions for the overall structure, such as general work elements involving tool motion limitations, reference aids, etc., similar to MIL-STDs should be developed and applied.

Analysis 130 - Task Panel Definition and Usage

a) Define representative task panel for use in 1-g environment. Determine how to effectively represent:
   - Work site environmental variables
   - Nature of task being studied
   - Nature of issues of interest

b) Develop methodology for task panel use.
   - Develop necessary specifications and procedures
   - Determine how to integrate lessons learned data
   - Determine how to integrate time delay treatments

Analysis 131 - User Compatibility Requirements Planning

Develop a plan to investigate user compatibility requirements (operator and customer) and to ensure identification and inclusion of user needs and requirements during concept development.
- Natural language interfaces
- System response time
- All other needs

Analysis 132 - Technology Development and Maintenance Support Planning

Formulate a technology development implementation plan to achieve a technology readiness for system upgrading and refurbishment periodically and a maintenance support plan to allow periodic preventive maintenance.

Analysis 133 - Fault Tolerant System Trade Analysis

Perform a trade analysis of cost versus reliability for fault tolerant system questions.

HUMAN FACTORS RESEARCH PLAN

INTEGRATED EXPERIMENTS

Experiment 101 - Establishment of Human Perceptual Capabilities and Limitations

Establish human perceptual capabilities and limitations as they relate to the specific teleoperator tasks and controls/display characteristics. Utilize a rough control station model.

- Vision
- Audition
  - Tonal
  - Speech
- Somasthetic
- Kinesthetic
- Extrasensory perception
- Subliminal cuing
- Cross-sensory interactions

Experiment 102 - Determination of Human Cognitive Styles, Performance Factors and Selection Criteria

a) Experimentally establish optimal human cognitive styles for teleoperator task performance utilizing an early, conceptually rough control station.

b) Analytically establish, with experimentation as necessary, how psychologically and physiologically imposed constraints impact operation performance on teleoperator tasks.
   - Work rest cycles
   - Learning
   - Training
   - Stress
   - Biorhythm disruptions
   - Work load

c) Define operator selection criteria in terms of the characteristics possessed by the individual, or those characteristics that can be developed through training, which ultimately affect system efficiency.
   - Aptitude
   - Biographical data
   - Geographical accessibility
   - Educational background
   - Work experience
   - Physical characteristics
   - Physiological characteristics
   - Psychological characteristics

Experiment 103 - Early Assessment of Operator's Display Information

a) Determine minimum amount of information to present to the operator for adequate task performance.

b) Assess alternative means of presenting the information to maximize performance. Consider relative benefits of:
   - Auditory versus visual information
   - Information complexity
     - Coding (symbolic and color)
     - Chunking
     - Formatting
   - Teleoperator sensory information presented to operator in same versus other sensory modality

The above assessments can utilize early control station concepts, similar to Experiments 101 and 102.

Experiment 104 - Late Assessment of Operator's Display Information

a) Determine minimum amount of information to present to the operator for adequate task performance.

b) Assess alternative means of presenting the information to maximize performance. Consider relative benefits of:
   - Auditory versus visual information
   - Information complexity
     - Coding (symbolic and color)
     - Chunking
     - Formatting
   - Teleoperator sensory information presented to operator in same versus sensory modality

This assessment requires a later model, higher fidelity control station than that utilized in Experiments 101, 102 and 103.

Experiment 105 - Applicability of Computer Aided Input Control Devices

Investigate applicability of computer aided control input devices with operator flexibility.
- Level of supervisory interaction
- Productivity enhancement

INTEGRATED TESTS

Test 101 - Operator Characterization for Optimal Control Station Design

a) Characterize the operator's anthropometry and biomechanical parameters with regard to the operational tasks to be performed in order to design the control station for optimal human performance.
   - Specialized operator pool identification/characterization
      - Functional (dynamic) dimensions
      - Structural (static) dimensions

b) Establish applicable anthropometric design guidelines.

Test 102 - Design Constraints Related to Human Information Limitations and Presentation Techniques

a) Establish the following through preliminary analysis and testing:

   1) Determine what information is used by operators to perform specific and complex tasks, establish performance changes with increased or decreased amounts of information, evaluate tradeoffs of cost versus performance benefit and evaluate means of presenting information.

   2) Determine how human information processing limitations (assimilation rates and capacities) impose constraints in control/displays designs; information presentation rates, format and coding; and automation alternatives.

b) Utilizing data derived in conjunction with a) above, analytically establish the following, with further testing as necessary:

   1) Establish optimum techniques and formats for presenting display symbolics to human operator.
      - Provide methodology for choosing symbols and display formats
      - Investigate alternatives in computer graphics representation

   2) Determine human operator variables and mental effects caused by symbolic representation of tasks.
      - Provide prior history on type, frequencies, and results attributed to human errors
      - Identify design factors in information display that tend to induce human errors

Test 103 - Controls/Displays Design Parameters

a) Determine the effects of input device capabilities on the operator performance quality.
   - Define range of task complexity at work site
   - Characterize representative set of operator commands
   - Compare input devices

b) Determine relative benefits in terms of operator performance of grouping controls/displays (C/D) according to various integration and design principles.
   - Function
   - Criticality
   - "Optimum" use (convenience, accuracy, speed, strength, etc.)
   - Sequence-of-use
   - Frequency-of-use
   - Combinations of above principles

c) Optimize C/D ratios empirically considering the complex interactions involved with type of control (knob, lever, pointer, cursors, etc.), precision and accuracy required, display size, tolerance, and time delays and operator performance requirements.

Test 104 - Time Delay Effects

Quantitatively establish human performance and physical/mental effects caused by time delay. Include estimation of time delay to be expected in space and ground data handling processes in addition to ground and space propagation delays.
- Magnitude dependency
- Task dependency
- System design effects
- Establish acceptability

Test 105 - Video Bandwidth Requirements

Establish the envelope of video system requirements for the various teleoperation tasks in order to specify the bandwidth.
- Mono/stereo usage
- Color/black and white
- Acceptable stereo second image degradation
- Image characteristics
- Frame rates
- Data compression schemes

Test 106 - Module Attachment Techniques

Establish module attachment techniques that enhance human performance of teleoperation activities.
- Stowage rack characteristics
- System design effects
- Optimum configuration

Test 107 - Mobility Design Parameters

a) Investigate attached mobility devices that show compatibility with remote human operator control ability.

b) Establish design parameters compatible with human control of teleoperators moving on or in space systems.
   - Space system configuration dependent
   - Investigate "natural" hard points
   - Propulsive redocking or crawling

Test 108 - Teleoperation Requirements and Design Guidelines

Establish the following through analysis with verification testing as required:

a) Requirements for teleoperated servicing:
   - Position versus rate controllers
   - Force/tactile sensor display
   - Onboard controller augmentation

b) Human engineering impacts on design parameters for interacting teleoperator devices at work sites of host spacecraft.
   - Concept/application acceptability
   - Establish alternatives
   - Feasibility of add-on docking points

Test 109 - Scene Illumination Requirements and Motion Effects

a) Determine the effects of scene illumination variables on the operator's performance ability.
   - Light sources
   - Scene characteristics
   - Interactions with target characteristics

b) Establish artificial lighting requirements.
   - Number and types
   - Control
   - Location
   - Low-level lighting

c) Establish motion levels between vehicles at which payload transfers are still feasible from a visual monitoring standpoint only.
   - Docked transfers
   - Undocked transfers

Test 110 - Attachment During Servicing, Component Replacement and Motion Effects

a) Establish motion levels between vehicles at which payload transfers are still feasible, from a manipulation standpoint. Note that vision effects are included in Test 109.
   - Docked transfers
   - Undocked transfers

b) Determine need for additional anchor arms/devices during servicing.
   - Task sensitivity dependent
   - Module add-on techniques

c) Investigate feasibility and acceptability of component replacement on orbit.
   - Size dependency
   - Accessibility to Orbital Replacement Unit (ORU)
   - Expert system contribution (CAD/CAM)
   - Remote end-effector dexterity
   - Contamination sensitivity

In the definition of test requirements for b) and c) above, note that these items were earlier addressed in Analysis 127.

Test 111 - Task Element Structure

Integrate the following elements into all other applicable tests to establish a wide variety of conditions for a final accumulated assessment:

a) Determine limits imposed on manipulator or tool motion by work site.

b) Determine suitability of coding and position reference aids for component identification, route mapping, and/or manipulator indexing.

c) Determine if a repertoire of well defined and structured "generic" work elements can be developed for assembly into a variety of sequences.

Test 112 - Material Transfer Mechanical Interface Parameters

Utilizing the earlier results of Analysis 125, verify the mechanical interface parameters needed to transfer materials/modules from spacecraft to teleoperator and vice versa.
- Degree of preparedness
- Transfer duration
- CG relation to grip points
- Optimum transfer paths