TELEOPERATOR SYSTEM MAN-MACHINE INTERFACE REQUIREMENTS FOR SATELLITE RETRIEVAL AND SERVICING

VOLUME II: DESIGN CRITERIA

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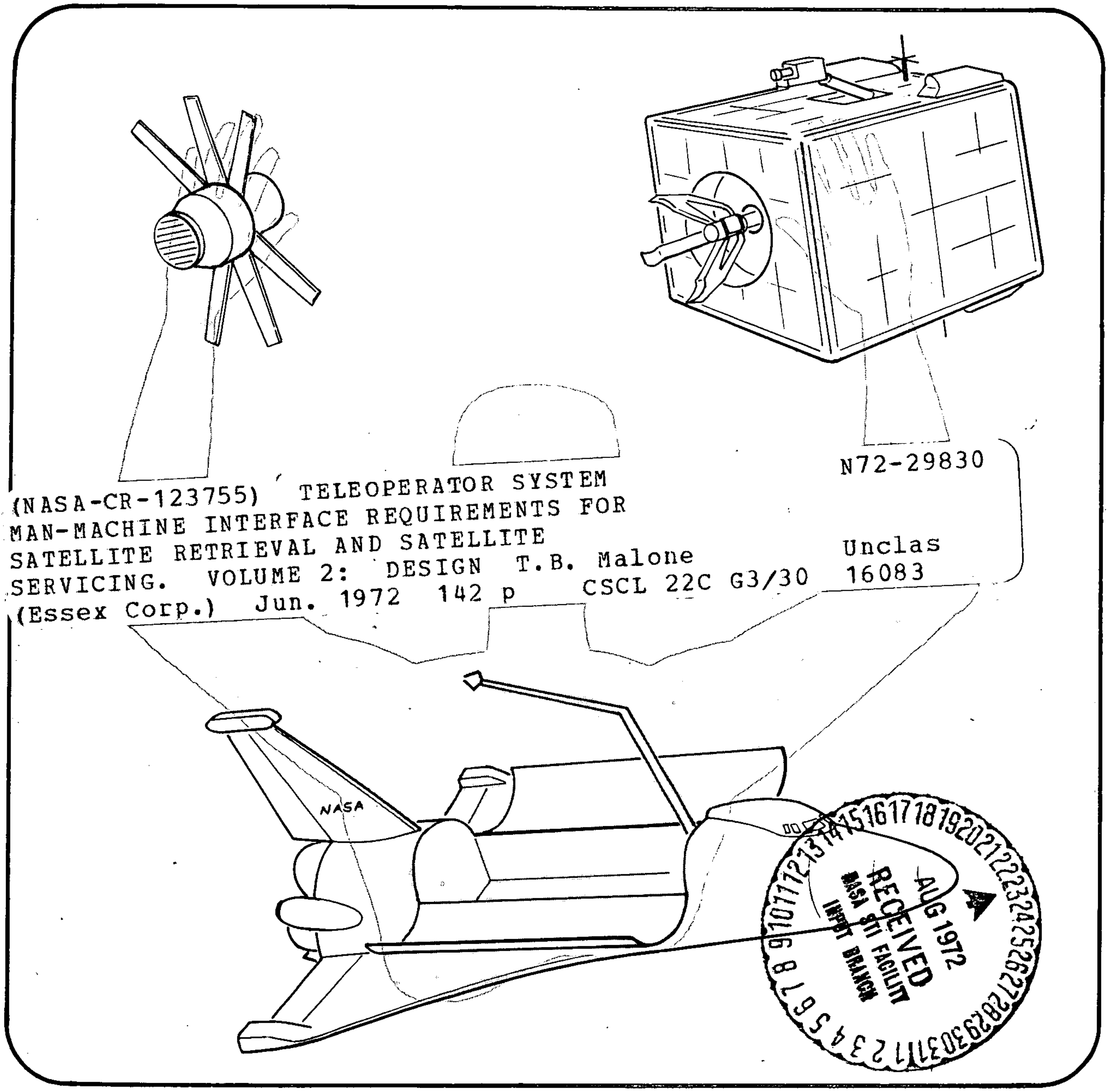

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TELEOPERATOR SYSTEM MAN-MACHINE INTERFACE REQUIREMENTS FOR SATELLITE RETRIEVAL AND SATELLITE SERVICING

Volume II - Design Criteria

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I

TABLE OF CONTENTS

Volume I

Chapter Page

Executive Summary i

1 Introduction 1

- Background
- Objectives and Scope
- Methodology
- Outputs

2 Mission Requirements 7

- Satellite Retrieval
- Satellite Servicing
- Satellites Selected for Study

3 System Requirements 19

- Satellite Retrieval
    - mission tasks
    - system requirements
- Satellite Servicing
    - mission tasks
    - system requirements

4 Man/Machine Functional Allocations 61

5 Control/Display Requirements 85

Volume II

Chapter

6 Operational Tradeoffs 100

7 Control System Tradeoffs 119

8 Visual System Tradeoffs 153

9 Auxiliary Sensor and Display Tradeoffs 180

10 Control and Display Design Requirements 184

TABLE OF CONTENTS - cont'd

Chapter | Page

11 Operator Requirements 190

- Workload Criteria
- Skills and Skill Levels

12 Additional Research and Advanced Technology Development Requirements 195

- Display
- Obstacle Avoidance
- Simulation Technology
- Control Systems
- Manipulator Evaluation

References 228

Executive Summary

A good deal of interest has been developing within NASA in providing the shuttle with a capability for retrieving and servicing automated satellites. In fact, a sizeable degree of the economic justification for the shuttle itself has been based on this specific capability. Investigations are proceeding to determine the impact of providing a retrieval and in orbit servicing capability to the shuttle on the economic and performance requirements of the satellites themselves. With the shuttle, satellites can be emplaced in orbit without requiring an expendable and dedicated boost vehicle. Satellites can also be replaced in orbit or a failed or obsolete spacecraft can be retrieved and returned to earth for refurbishment. Having the shuttle in orbit also enables the repair, maintenance, update, resupply, and refurbishment of satellites on orbit, all of which functions have been included in the generic term, satellite servicing.

The likely candidate system to perform satellite retrieval to the shuttle and satellite servicing on orbit is the teleoperator. This system basically entails a remotely controlled mobility unit with manipulators and sensors to perform the required mission operations. The system includes man in the control loop either serving as the primary source of control input or as a supervisor of computer control. Finally, the system includes a communication and data link between the manipulators, effectors, and sensors at the worksite, and the man at a remote location.

The rationale for considering the use of a teleoperator for satellite retrieval and servicing missions is basically that it is the most effective means of successfully completing the missions. Satellite mass and astronaut safety considerations obviate the use of EVA for satellite retrieval. Astronaut safety considerations and required workload make EVA for satellite servicing less attractive. Requirements for adaptive control and degree of system complexity reduce the effectiveness of completely automated systems for both retrieval and servicing. The teleoperator, however, has the basic advantages of the EVA approach (use of man's adaptive intelligence and sensory capabilities) while ensuring astronaut safety and requiring less complexity than an automated approach.

With its heavy reliance on the capabilities of the human operator in the control system, the teleoperator has been described as a system which serves to extend and enhance the natural sensory, manipulative, locomotive, and cognitive capabilities of man. If this is a valid description, it necessarily follows that one of the more important considerations in the definition of a teleoperator system is the man-machine interface. This interface includes the aspects of the hardware and software design which interact with the man as well as the aspects of the man himself which impact his ability to interact with the machine (skills and skill levels, and workload). Specification of requirements for the man-machine interface entails the development of system requirements, the integration of these requirements with relevant capabilities and limitations of the human operator, and the determination of methods to satisfy the requirements taking full advantage of man's capabilities and within the constraints imposed by his limitations.

The objective of this investigation was to analytically develop requirements for the man-machine interface for a teleoperator system performing on-orbit satellite retrieval and satellite servicing. Requirements are basically of two types: mission/system requirements, and design requirements or design criteria.

Two types of teleoperator systems were considered in the study: a free flying vehicle; and a shuttle attached manipulator. The free flyer comprised a separate vehicle deployed by the shuttle carrying its own propulsion, power, manipulators, and sensors. The shuttle attached manipulator system included one or two long (up to 50 feet) boom manipulators with sensors and end effector devices attached. Throughout the study no attempt was made to evaluate the relative effectiveness or efficiency of these two system concepts. It was assumed at the outset that one or both could be incorporated in any specific shuttle mission and, therefore, requirements and design criteria for both will be needed.

The methodology used in the study entailed an application of the Essex Man-Systems analysis technique as well as a complete familiarization with relevant work being performed at government agencies (notably NASA) and by private industry. While the investigation was analytic and did not result in the acquisition of any additional data through experimentation, it did rely heavily on the findings and conclusions of past and on-going empirical studies of remote manipulator system requirements. The investigation of teleoperaotr man-machine interface requirements for satellite retrieval and servicing also logically proceeded from an earlier effort performed by the author for NASA (Malone, 1971). This earlier study was concerned with specifying requirements for additional human factors research and advanced man-machine interface technology development for space teleoperator applications.

The present study initially identified satellite retrieval and satellite servicing mission requirements and identified five satellites selected as being representative of the population of spacecraft projected for the period 1973-1985. The next step entailed developing system requirements for three system/mission combinations (free flyer satellite retrieval, attached manipulator satellite retrieval, and free flyer or attached manipulator satellite servicing). Identification of system requirements began with a development of functional requirements. For the satellite retrieval mission a total of 14 basic functions were identified which were further analyzed to about 180 subfunctions or tasks. In the analysis of the satellite servicing mission, three basic functions were identified which were further resolved into a total of 37 tasks.

Specific requirements were then generated for each task in each mission. These requirements included:

Information Requirements - information needed by the system to perform the task

Performance Requirements - capabilities required of the system to successfully complete the task

Support Requirements - capabilities required of other systems

Interface Requirements - physical, procedural, and environmental interfaces required

The identification of specific requirements relied heavily on the results of earlier investigations, notably the Bell Aerospace MSFC studies, the GE MSC and ARC investigations, the North American Rockwell ATS-V study, the Grumman MSFC Docking study, the Martin and MBA attached manipulator work, the MDAC Shuttle Orbital Applications and Requirements (SOAR), the MIT control studies for MSFC, the Lockheed Payload Effects Analysis, General Dynamics studies for the Office of Naval Research, and in house study efforts performed at MSFC and MSC. Where available and relevant, performance requirements for the retrieval and servicing missions were obtained from these sources. Due to variations in the subject missions and system techniques, these requirements are not meant to isolate the precise capabilities required of a teleoperator. Rather they are indicative of the range of required values which might be encountered in typical retrieval or servicing missions.

The above discussion serves to point up an immediate and critical problem in the development and integration of technology for teleoperator systems. Maximum levels of effectiveness and economy in design are realized when the design efforts are focussed and directed by clearly defined and

and quantitatively described performance requirements. The best approach to design a system to do what must be done is to first of all define in precise terms what must be done, i.e., the performance requirements. These requirements identify the capability which the system must possess. They must be reliable, accurate, quantitative, and unambiguous. Developing such requirements is the first order of business of personnel engaged in developing teleoperator systems technology. The URS/Matrix Corporation is currently performing a study for MSFC to establish such requirements.

When system requirements have been identified and analyzed, they must be integrated. This process assures that priorities are considered and that incompatibilities and inconsistencies existing among different requirements are eliminated.

The next step was then to develop guidelines for allocating system functions to man or machine performance, for each mission. This tradeoff was based on the integration of requirements and the relationship between these requirements and human capabilities and limitations on the one hand, and between the requirements and engineering considerations on the other (complexity, state-of-the-art technology, reliability, etc.). The allocation developed in this study were such that the satellite servicing system is basically a manual system, the free flyer satellite retrieval system is primarily machine-aided (computer aided or supervisory control).

Again based on the results of the requirements analysis, a series of other operational tradeoffs were performed. The results of these trades were as follows:

Number of operators	- all systems and missions - one
Location of operator	- Free Flyer - sortie module - Attached - shuttle
Free Flyer ranging	- provision of range and rate sensor
Measurement of satellite rotational parameters	- video aids and special sensors

Free Flyer tracking of satellite attach point	- unresolved between manual or automatic and between grappler tracking vs whole vehicle tracking
Free Flyer station keeping	- unresolved between manual and automatic control
Satellite contact	- single point contact
Attached manipulator position monitoring	- direct view and video
Attached manipulator number of arms	- one for satellite contact - one for satellite emplacement into bay
Mode of emplacement	- automatic or computer assist
Type of servicing manipulators	- unresolved between special and general purpose
Number of servicing manipulators	- one
Type of modules to be serviced	- standardized
Stabilization at the worksite during servicing	- additional arm(s)

Design criteria were then developed for the control system of the teleoperator. These criteria were in three basic areas: controllers; control sharing for mobility and manipulative activities; and video control.

The essential capabilities and limitations of seven different controller configurations were identified and analyzed. This process led to the elimination of three concepts: the switch box; the exoskeleton; and a separate joystick and switchbox. The remaining concepts included an integrated joystick/switch arrangement, a pivoted joystick, the MIT isometric controller, and the Martin Mechanical Analog. An attempt was made to further reduce this list of competing candidates for each system/mission combination by comparing the performance requirements with the capabilities of each configuration. However, based on the inadequacy of existing information concerning the relative importance of the separate requirements and the specific capabilities of the concepts, in quantitative terms, no such selection was possible. All that can be said at present is that the selection of a controller must be made within the framework of the requirements associated with the specific mission, and must be based on man-in-the-loop simulation of that mission.

In terms of mobility unit-manipulator control sharing, no problems were identified for the attached system. For the free flyer satellite retrieval, it is recommended that techniques of computer assisted control be investigated to reduce the workload on a single operator controlling both functions simultaneously. It can be stated that if a computer assist capability is not provided, serious consideration must then be given to increasing the crew size from one to two men for the free flyer satellite retrieval mission.

No requirements for head aimed or eye aimed TV were evidenced for the subject missions. The recommended mode of video control is therefore manual control.

In the display area specific design requirements were developed for the primary display system - the visual system. These requirements can be summarized as follows:

- Use of four 11-inch 525 2D monitors with two receiving video from the teleoperator, one receiving video from the shuttle, and one dedicated for computer generated display
- Use of a single 44° field of view or a selectable 44° and 10° field
- Video size resolution - 5 arc minutes
- Video motion resolution - 5 arc minutes/sec
- Depth of view - two 2D cameras to provide three axis orientation
- Frame rate - at least 30 frames per second
- Lighting - adjustable up to 100 ft. lamberts on the screen. Requires 50,000 ft. candles at 20 feet from the target.

- No specific requirements for force feedback have been identified
- Manipulator position - video of arm and computer generated display and advisory indicators.

In terms of operator workload it was determined that the free flyer satellite retrieval mission was the most demanding with the satellite servicing mission requiring the smallest load. In terms of skill requirements, the most important skill areas, in order of importance, are as follows:

- manipulator operation
- docking control
- image interpretation
- data handling and integration
- troubleshooting - fault isolation

The last task in this study was to identify requirements for additional research and technology development. Much research is needed to resolve unanswered questions concerning operator capabilities and system requirements. In technology development, additional effort is needed in manipulator and effector development and evaluation, display integration, controller design, computer assisted control techniques, special sensors and display aids, and methods for quantifying operator workload.

The conclusions of the study can be summarized as follows:

- Human operators can effectively participate in satellite retrieval and servicing missions using teleoperators providing that adequate attention is given to the design of the man-machine interface.
- Use of a single operator in orbit should be a design goal for reasons of space requirements, control integration and continuity, and demands of operator selection and training. This will necessitate investigation of computer assisted control techniques primarily for satellite retrieval missions.
- Man-machine interface design must be based on a careful and complete understanding of system performance requirements for the specific mission.

- No requirements are apparent, based on existing evidence, for inclusion of stereo TV, head or eye aimed TV, dual field of view, and kinesthetic feedback of arm position (exoskeleton controller).
- A range and range rate sensor will be needed in the free flyer system primarily to reduce operator workload and to ensure mission success.
- For satellite capture, single point contact is recommended based on man-machine considerations.
- A single manipulator arm is sufficient for satellite servicing.
- Spacecraft modules to be serviced should be standardized in terms of attach point design and location and markings.
- A good deal of work remains to be done before the precise design requirements for the man-machine interface of a teleoperator system can be specified. This work will essentially involve the conduct of man-in-the-loop simulations of selected sequences of each mission.

This report of work conducted in this study is organized into two separate volumes. Volume I presents the results of the analysis of requirements. Volume II is concerned with the descriptions of design criteria and requirements for additional research.

See table of contents
Volume 2 begins with page 100

CHAPTER 6 OPERATIONAL TRADEOFFS

In the development of design requirements for the teleoperator system man-machine interface, certain assumptions and decisions must be made concerning the system itself. Since this study is concerned with human factors aspects of the teleoperator systems rather than the entire system, these assumptions must be based on requirements oriented toward the man in the system rather than on criteria established for the total system.

The initial tradeoff decisions concerned the role of man in each of the two systems (free flyer and shuttle attached) for each of the two missions (satellite retrieval and satellite servicing). These were described in Chapter 4 of Volume I as allocations of system functions to man on machine (Tables 26 and 27). The allocations of functions were made based on existing information concerning operator capabilities and limitations, existing state of the art technology, operator workload, performance accuracies required, and operational and engineering complexity. The results of the allocations for each system and mission are presented in Table 32 as percentages of the mission tasks allocated to each allocation category.

TABLE 32

PERCENTAGE OF MISSION TASKS FOR EACH SYSTEM
ALLOCATED TO EACH CATEGORY

Mission/System	Allocation Category Manual	Man-aided	Machine-aided	Automatic
Satellite Retrieval - Free Flyer	45%	40%	15%	0%
Satellite Retrieval - Attached	10%	65%	25%	0%
Satellite Servicing - Free Flyer and Attached	100%	0%	0%	0%

While satellite servicing is seen to be a strictly manual operation, satellite retrieval using either system will require extensive use of aids and more or less computer assisted control. The tasks for free flyer retrieval requiring computer assisted control include rate synchronization, identification of axis of rotation, and control of the actual despin.

The primary rationale for specifying a requirement for computer interface in the retrieval mission with the attached teleoperator was the conclusion that simple manual control may be inadequate, primarily in the recovery phase where the satellite is translated to the cargo bay. This conclusion was based on informal discussions with cognitive personnel at Grumman Aerospace, North American Rockwell, and the Manned Spacecraft Center, and on documentation prepared by Martin Marietta, North American Rockwell, and MB Associates. The North American Phase B Shuttle report indicates that, in their attached teleoperator design concept, three modes of manipulator control are provided: 1) manual control, 2) preset control of arm position angles and 3) fully automatic control and sequencing of arm positioning, engagement, and release using the flexible command programming capability of the orbiter's computer. In their recently completed study of requirements for assembly and docking of spacecraft in earth orbit, for MSFC, Grumman Aerospace has begun to identify potential problems for manual control of a three joint attached boom retrieving a payload to the shuttle or space station. The basic problem is the simultaneous control of the six degrees of freedom of each of two arms to effect a smooth, accurate and effective recovery.

A second reason for considering computer input to the control of attached teleoperator systems, primarily in the recovery phase of a retrieval mission when docking or grappling has already been accomplished, is the fact that all parameters of manipulator position, rate, acceleration and force/torque applications are known by virtue of the direct hard link between manipulator and shuttle. It should therefore present no real problem to develop software to enable a computer to accurately index the joint angles, rates and torques, arm position and orientation and tip position in three dimensional coordinates with respect to a reference point fixed on or in the shuttle. From there, the computer could provide control information to the man for manual input or computer input via supervisory techniques, or the computer could control the recovery automatically with the man monitoring and equipped with override capability.

The problem of computer assisted control prior to docking is more complex since all important variables may not be known to any great accuracy (target position in three dimension with respect to the tip of the manipulator). In their development of requirements for a Space Station Assembly and Cargo Handling System for MSC, MB Associates (1971) have recommended the use of computer assisted manipulator control and have classified four types of such control as:

- computer assisted end point vectoring
- computer follower using an analog of the manipulator as the control device
- supervisory control where man provides inputs and updates to computer command position
- preprogrammed or automatic control

Similarly, Martin Marietta in their attached manipulator study for MSC (1971) has identified three control modes which require some degree of computer interface for control input. These include:

- position indexing
- coordinate transfers based on TV or shuttle axes
- computer preprogram

Although the exact form of computer assisted control of attached manipulators remains to be developed, generally most of the organizations concerned with designing control systems for attached teleoperators express the requirement for some degree of computer involvement. Research has been proceeding for some time at MIT and Case Western Reserve among others to define the problem and to develop mathematical solutions. The approach has generally been to develop path finding algorithms to solve the arm position and joint angles required to place the tip at a specified location in a determined orientation. Much of this work has been more applicable to control with time delay than with direct manipulator real time control.

The advantages of computer aided manipulator control over manual control were described by Diederich (1970) as including the following:

- reduction of the amount of conscious attention required of the operator to control the path or position of the manipulator
- enhancement of the performance of positioning operations by optimization of terminal configurations of the manipulator
- improvement of the speed and accuracy of path control operations
- minimization of the amount of data the operator is required to specify in order to perform a task.

In addition to decisions of type of control, other important operational tradeoffs include the choice of number of operators, location of the operators, and the relative effectiveness of specific options for each mission - system combination.

1. Number of operators

A tradeoff was performed for each mission - system combination wherein the relative effectiveness of alternate operator configurations was judged on a set of 11 criteria. The criteria included:

Complexity - operational and engineering complexity

Performance accuracy - degree to which requirements are met

Nominal workload - workload on the operator(s) in nominal modes

Contingency workload - workload in failure modes

Volume requirements - space needed in the shuttle to accomodate the operators

Support requirements - special links, aids, and information

Computer requirements - degree to which computerization is required

Flexibility - degree to which all requirements are accomodated

Integration of control - degree to which control requirements can be integrated

Integration of display - degree to which information requirements can be integrated

Special skills - requirements for special skills on the part of the operator

In each mission - system combination alternate operator configurations (single operator-manual, dual operator, etc.) were ranked in terms of their relative performance or effectiveness on each criterion. The results of these analyses are presented in Table 33. As indicated in this table, the optimal approach for each mission - system combination was as follows:

Satellite Retrieval/free flyer - single operator - basically manual
Satellite Retrieval/attached - single operator - computer assisted
Satellite Servicing - single operator - manual

It should be emphasized that the criteria used in these tradeoffs were essentially factors associated with the man-machine interface. No consideration was given to such drivers as cost, weight, power, etc. Based on these tradeoffs it is recommended that single operator control be considered for satellite retrieval and servicing missions when operating from the shuttle.

2. Operator location

The operator of the teleoperator can be located in the sortie module in the shuttle bay, in an extended but attached sortie can, in the shuttle cabin,

TABLE 33

RELATIVE RANKING OF ALTERNATE OPERATOR CONFIGURATIONS ON EACH CRITERION MEASURE FOR EACH MISSION/SYSTEM

	Complexity	Performance Accuracy	Nominal Workload	Contingency Workload	Volume Requirements	Support Requirements	Computer Requirements	Flexibility	Integration of Control	Integration of Displays	Special Skills	Sum	Rank
<u>Satellite Retrieval - Free Flyer</u>													
Single operator - manual	1	1	4	3	1	1	1	2	1	1	2	18	1
Single operator - computer assisted	3	2	1	4	1	2	4	4	2	2	1	26	2
One man controlling the vehicle and one for the grappler	2	3	2	1	3	3	2	1	3	3	3	26	2
Three man team (NR ATS-V)	4	4	3	2	4	4	3	3	4	4	4	39	4
<u>Satellite Retrieval - Attached</u>													
Single operator - computer assisted	1	1	2	3	1	1	1	3	1	1	1	16	1
One man controlling the arm and one monitoring	2	2	1	1	2	2	2	2	2	2	2	20	2
Two men controlling each of two arms	3	3	3	2	3	3	3	1	3	3	3	30	3
<u>Satellite Servicing</u>													
Single operator - manual	1	4	4	2	1	1	1	1	1	1	4	21	1
Single operator - computer assisted	3	3	3	3	3	2	3	3	2	2	3	30	3
One operator controlling and one monitoring	2	2	2	1	4	4	2	2	3	3	2	27	2
Automated servicing	4	1	1	4	1	3	4	4	4	4	1	31	3

Note: Numbers refer to relative performance with 1 indicating best performance, 2 next best, etc.

in the tug or on earth. A tradeoff of these locations for each mission - system combination was made. The criteria for these tradeoffs were the same as those used for number of operators with the addition of three factors: operator safety, shuttle interface, and use of state-of-the-art technology.

The results of the tradeoffs are presented in Table 34. Based on this data it can be concluded that for free flyer missions the best location for the man is in the sortie can, either in the bay or extended. For shuttle attached missions the optimal location for the operator is clearly in the shuttle cabin. The reason for this is essentially that the provision of a direct view of the manipulator is most easily implemented for the man in the shuttle. This approach is already being baselined by MSC for the shuttle cargo handling system.

3. Free Flyer Satellite Retrieval Operational Tradeoffs

In considering the requirements for the man-machine interface for a free flyer satellite retrieval, certain operational decisions must be made. These essentially include selection of the technique to perform:

- Ranging
- Measurement of satellite rotational rates
- Tracking the attach points on a rotating satellite
- Station keeping
- Satellite contact
- Grapple rotating satellite
- Despin force application
- Force-torque sensing
- Satellite preparation-safeing

This selection was based on a consideration of factors primarily

TABLE 34

RELATIVE RANKING OF ALTERNATE OPERATOR LOCATION ON EACH CRITERION MEASURE

	Complexity	Performance Accuracy	Workload	Volume Requirements	Support Requirements	Computer Requirements	Flexibility	Control-Display Rqmts	Special Skills	Safety	Shuttle Interface	State of the Art	SUM	RANK
<u>Satellite Retrieval and Servicing - Free Flyer</u>														
Sortie can in bay	1	3	3	1	1	1	3	3	1	3	3	1	24	1
Sortie can extended	2	1	2	1	4	1	1	1	1	4	4	1	23	1
Shuttle Cabin	3	2	1	1	3	1	2	2	1	2	5	3	26	3
Tug	4	4	4	4	5	5	4	5	5	5	2	5	52	5
Earth	5	5	5	5	2	4	5	4	4	1	1	4	45	4
<u>Satellite Retrieval and Servicing-Attached Manipulator</u>														
Sortie can in bay	2	3	3	3	3	1	3	3	3	3	2	2	31	3
Sortie can extended	3	2	2	2	2	1	2	2	2	4	3	3	28	2
Shuttle Cabin	1	1	1	1	1	1	1	1	1	2	1	1	13	1
Tug	4	5	5	5	5	4	4	4	5	5	5	5	56	5
Earth	5	4	4	4	4	5	5	5	4	1	4	4	49	4

concerned with the man-machine interface and operator requirements. Alternate approaches for each operational requirement listed above were ranked in terms of relative effectiveness on the following criteria:

- Complexity
- Performance accuracy
- Time to perform
- Workload on the operator
- Control-display requirements
- Computer requirements
- State-of-the-art-technology
- Flexibility
- Requirements for special skills

The results of the tradeoffs on each operational requirement are present in Table 35. The results of the tradeoff are summarized below.

Ranging - from a man-machine standpoint, a range and range rate sensor is required to display range and rate directly to the operator. The points in the mission where such data are deemed important are at the initial input of a closing velocity, at maximum range, and in the final docking sequence, at close range. It should be emphasized that this decision does not imply that the ranging operation is impossible without the sensor. Using video alone an operator can adequately establish the range and relative rate of the teleoperator to the target. Studies conducted by Bell Aerospace for MSFC (1972) on free flying teleoperator performance capability, and by North American Rockwell (1971) for rendezvous and despin of ATS-V indicate that an operator performed essentially as well using video alone as when he was provided video and range displays in terms of miss distance and closing velocity. Performance with the video alone mode was generally less accurate for control of angular rates. The primary

TABLE 35

RELATIVE EFFECTIVENESS OF FREE FLYER SATELLITE RETRIEVAL SYSTEM ON MAN-MACHINE FACTORS AND OPERATOR REQUIREMENTS

Operational Requirement/Options	Complexity	Accuracy	Time	Workload	Control/Display Requirements	Computer Rqmts	State of the Art	Flexibility	Special Skills	Sum	Rank
Ranging											
Video alone	2	6	7	8	3	1	1	3	8	39	6
Video-Satellite aids	3	5	5	7	1	1	3	6	6	37	3
Video stereo	4	7	6	5	7	6	7	4	4	49	8
Integrated ΔV	5	8	4	4	3	7	2	5	5	43	7
Shuttle Ranging	1	1	1	1	8	4	5	7	1	29	2
Range/Rate Sensor	7	1	1	1	3	5	5	1	1	25	1
Rate Sensor	6	4	3	6	3	1	4	2	7	36	3
Auto Ranging	8	1	1	1	1	8	8	8	1	37	3
Measure Satellite Rotational Rates											
Video Aid	1	4	4	4	2	1	1	1	2	20	1
Camera Rotation	3	2	3	3	3	1	1	2	4	22	3
Stroboscope	2	3	2	2	4	1	3	3	3	23	3
Special Sensor	4	1	1	1	1	4	3	4	1	20	1
Track Attach Points on Rotating Satellite											
Manual grappler track	1	3	1	3	4	1	1	2	4	20	1
Manual vehicle track	2	4	2	4	3	1	1	1	3	21	1
Auto grappler track	3	1	3	1	2	3	3	4	2	22	1
Auto vehicle track	4	2	4	2	1	3	4	3	1	24	4
Station Keeping											
Manual	1	2	2	2	2	1	1	1	2	14	1
Automatic	2	1	1	1	1	2	2	2	1	13	1
Achieve Contact with Satellite											
Manual grasp	1	1	3	3	3	1	1	1	3	17	2
Auto-on man signal	2	2	2	2	2	1	1	2	1	15	1
Auto-on contact signal	3	3	1	1	1	1	3	3	1	17	2
Grab Rotating Satellite											
Single point contact	1	1	2	1	1	1	1	1	1	10	1
Two point-one grappler	4	2	3	2	2	1	2	2	2	20	2
Two point-two grapplers	5	5	5	4	4	1	4	3	5	36	5
Three point contact	6	6	6	5	6	1	5	4	6	45	6
Balloon insertion	3	3	4	3	3	1	6	6	3	32	3
Probe-drogue docking	2	4	1	6	5	1	3	5	4	31	3

Table 35 Continued

	Complexity	Accuracy	Time	Workload	Control/Display Requirements	Computer Requirements	State of the Art	Flexibility	Special Skills	Sum	Rank
Apply Despin Force											
Reaction control	1	3	3	3	3	3	1	2	3	22	3
ATS-V despin cage	2	1	2	1	1	1	2	3	2	15	1
Grappler rigidization	3	2	1	2	2	1	3	1	1	16	1
Force-Torque Sensing-Despin											
Video	1	4	4	1	1	1	1	4	4	21	3
Force feedback	4	3	2	2	4	2	4	3	3	27	4
Force readout	2	2	2	3	2	3	2	2	2	20	2
Force/rate readout	3	1	1	3	3	3	2	1	1	18	1
Satellite Preparation - Safeing											
Automatic in satellite	3	1	1	1	1	3	3	3	1	17	1
Preprogrammed - manipulator	2	2	2	2	2	2	2	2	2	18	1
Manual - manipulator	1	3	3	3	3	1	1	1	2	18	1

impact of not providing range and range rate directly to the pilot is a higher workload, greater skill requirements, and greater performance time. With single operator control of the free flyer, provision of range and range rate data is therefore recommended.

Measurement of satellite rotational rates - the selected techniques for this operation are either use of video aids or use of a special sensor. In the NAR ATS-V study the rate was estimated by sensing reflected sunlight and driving an oscilloscope with the pulse. The docking cage was spun up to match the ATS-V rate by matching the cage rate with the pulse rate on the scope, and by rotating the video view. In this mission the requirement was to match the ATS-V rate to an accuracy of ± .1 percent of the actual rate. With an ATS-V spin rate of 73 rpm, this accuracy requirement is ± .073 rpm. The .073 rpm resolves to .0073 radians/sec or about 25 arc minutes/sec which is more than adequate for human operator detection of motion (threshold under ideal laboratory conditions is about 5 arc minutes/sec.) It is concluded that, even with accuracy requirements as stringent as those posed for the ATS-V despin mission, the pilot can effectively perform given adequate video aids (reference markers) and/or special sensor data.

Track attach points on rotating satellite - the options for this requirement were essentially two: tracking the path of the rotating or nutating attach point with the grappler arm or with the total vehicle; and manually controlled vs automatic tracking with manual update. The results of the tradeoff indicate that, based on existing data, equal performance can be expected of the manual grappler tracking, manual vehicle tracking, and automatic grappler tracking. Additional research is required to resolve this selection. The primary problems with grappler tracking in a manual mode are obtaining a video view of both the rotating grappler end effector and the attach point, and the workload of maintaining vehicle position relative to the target while simultaneously controlling the grappler. Problems with automatic grappler tracking include time for operator intervention and loss of control flexibility. Problems with vehicle tracking are accuracy degradations and high workload.

Station keeping - Based on existing data, no clear superiority was noted for either automatic or manually controlled station keeping. The automatic mode requires a range and rate sensor and an interface between the sensor and the control logic. The manual mode results in a higher workload and time to perform and lower accuracy.

Achieve contact with the satellite - The selected technique for grasping the satellite attach point was an automatic, full on grasp based on a manual command. This approach is also recommended by Bell Aerospace in their ongoing free flyer system experiment definition study for MSFC.

Grab rotating satellite - In the Bell experiment definition study a number of grappler concepts are presented which range from single point contact (ball joint), to two or three arms, to use of a balloon device. The man-machine interface tradeoff indicated that, from an operator point of view, the single point contact approach was clearly superior. This approach is being further investigated in in-house studies of satellite retrieval at MSFC.

Apply despin force - From a human factors standpoint, the use of an ATS-V like docking cage and rigidization of a grappler arm were equally effective and superior to use of RCS for despin.

Force-torque sensing-despin - Providing the operator with a force-rate readout was selected as the optimum approach for monitoring despin operations. Use of video alone was judged inadequate due to accuracy and performance time problems. Force feedback was discarded due to complexity and control-display problems as well as technology development requirements. Use of a force display alone was judged ineffective due to additional requirements placed on the operator to resolve force to resultant rate.

Satellite preparation - safeing - No decision was made for the method of satellite safeing. Additional data are required reflecting the relative performance of each option.

4. Attached Manipulator Satellite Retrieval Operational Tradeoffs

The operational tradeoffs for the attached teleoperator were conducted for the following operational requirements:

- Monitor manipulator position
- Contact satellite
- Emplace satellite in bay

Results of the tradeoffs are presented in Table 36. A discussion of these results is presented below:

Monitor manipulator position - The selected technique was use of a direct view with video. The only disadvantage of this approach was in complexity, in that the operator must coordinate views from two different media. The use of video alone, on the arm and on the shuttle was seen to have no serious problems. However, compared with the use of a direct view with video it failed to exceed that approach on any of the criteria.

Contact satellite - The recommended approach from a man-machine standpoint is the use of one arm. This approach significantly reduces the workload, complexity, and special skill requirements placed on the operator. It is in keeping with the results of investigation, conducted by MBA and Martin Marietta (both in 1971) on development of a conceptual design for an attached manipulator system.

TABLE 36

RELATIVE EFFECTIVENESS OF SATELLITE RETRIEVAL ATTACHED SYSTEM OPTIONS ON MAN MACHINE FACTORS AND OPERATOR REQUIREMENTS

Operational Requirement/Option	Complexity	Accuracy	Time	Workload	Cont./Disp. Rqmts.	Computer Rqmts.	State-of-the-art	Flexibility	Special Skills	Safety	Sum	Rank
Monitor Manipulator Position												
Video from Shuttle	1	3	3	2	4	1	1	4	3	4	26	3
Video on Arm	2	4	4	2	5	1	5	3	4	5	35	5
Video-Shuttle and Arm	3	2	2	2	3	1	1	2	2	3	21	2
Direct View Alone	4	5	5	1	1	1	4	5	5	2	33	4
Direct View and Video	5	1	1	2	2	1	1	1	1	1	16	1
Contact Satellite												
One Arm Grapple	1	2	1	1	1	1	1	3	1	2	14	1
One Arm Grapple - One Arm Video	2	1	2	2	2	2	2	2	2	1	18	2
Two Arm Grapple	3	3	3	3	3	3	3	1	3	3	28	3
Emplace Satellite in Bay												
One Arm Manual	1	6	5	5	5	1	1	1	5	5	35	3
Two Arms Manual	2	5	6	6	6	1	1	4	6	6	43	6
One Arm Computer Assist	3	4	2	3	2	2	1	2	2	2	23	1
Two Arms Computer Assist	4	3	4	4	4	3	5	5	4	4	40	5
One Arm Automatic	5	2	1	1	1	4	4	3	1	1	23	1
Two Arms Automatic	6	1	3	2	3	5	6	6	3	3	38	4

Emplace satellite in bay - The selected options were one arm automatic control or one arm computer assisted control. These approaches performed well on technology requirements, safety, special skills, control-display requirements, time to perform, and workload.

5. Satellite Servicing Operational Tradeoffs

Operational requirements investigated for satellite servicing included the following:

- Removal and replacement
  - Type of manipulator
  - Number of manipulators
  - Type of modules
- Stabilization during servicing
- Worksite preparation

Results of the tradeoffs are presented in Table 37. A discussion of these results is presented below.

Removal/Replacement - manipulator - No decision was made between use of special purpose and general purpose manipulators. It is evident that in some situations (unprepared worksite, unstandardized modules, etc.) use of general purpose devices would prove superior, while in other conditions (standardization of worksites and modules) special purpose manipulators would excel. The tradeoff of these options is therefore meaningless. All that was really learned from this trade was that use of special purpose or general purpose satellite servicing manipulators was superior to use of the retrieval grappler for satellite servicing.

TABLE 37

RELATIVE EFFECTIVENESS OF SATELLITE SERVICING OPTIONS FREE FLYER AND ATTACHED

Task/Options	Complexity	Accuracy	Time	Workload	Cont./Disp. Rqmts.	Computer Rqmts.	State-of-the-art	Flexibility	Special Skills	Sum	Rank
Remove and Replace - manipulator											
Using Retrieval grappler	1	3	3	3	2	1	2	2	1	20	3
General purpose manipulator	2	2	2	2	3	1	1	1	2	16	1
Special purpose device	3	1	1	1	1	3	3	3	1	17	1
Remove and Replace - number of manipulators											
Single manipulator	1	2	1	1	1	1	1	2	1	11	1
Two manipulators	2	1	2	2	2	1	1	1	2	14	2
Remove and Replace - modules											
Standardized modules	1	1	1	1	1	2	2	2	1	12	1
Non-standardized modules	1	2	2	2	2	1	1	1	2	14	2
Stabilization Druing Removal/ Replace											
No hard contact	1	4	4	4	4	1	3	3	4	28	4
Use retrieval grappler	2	3	2	1	1	1	1	4	2	17	2
Provide additional arm(s)	4	1	1	2	2	1	2	1	1	15	1
Two arms - one working one holding	3	2	3	3	3	1	4	2	3	24	3
Worksite Preparation											
Site already prepared	1	1	1	1	1	1	3	3	1	13	1
Site prepared automatically	3	2	2	2	2	3	2	2	2	20	2
Site prepared manually	2	3	3	3	3	1	1	1	3	20	2

Removal/Replacement - number of manipulators - Use of one manipulator was seen to be superior to the use of two arms from a man-machine viewpoint. This substantiates an inference which can be drawn from the Bell Aerospace free flyer study for MSFC (1972) that satellite servicing tasks could be performed as effectively with one arm as with two.

Removal/Replacement - type of modules - Use of standardized modules was judged to be superior to use of non-standardized equipment.

Stabilization during servicing - The optional approach for vehicle stabilization is to provide an additional arm or arms for that purpose. The use of the retrieval grappler suffered from a lack of flexibility.

Worksite preparation - The site should be prepared in advance of the servicing mission.

Summary

Based on these tradeoffs, the recommended approach for each mission - system combination is as follows:

Satellite Retrieval - Free Flyer

Single operator located in Sortie can

Manual control of grappler

Range and range rate sensor and display

Video aid or special sensor to measure target rates

Manual grappler or vehicle tracking or automatic grappler tracking of attach point

Manual or automatic station keeping

Automatic capture based on manual input

Single grappler single point contact for satellite capture

Use of arm rigidization or motor driven cage for despin

Force sensing by means of force/rate readout

Satellite Retrieval - Attached

Single operator in shuttle

Manual and computer assisted control - overall

One arm computer assisted or automated satellite emplacement

One arm grappler

Direct view and video view of target

Satellite Servicing

Single operator, in shuttle for attached, in Sortie can for free flyer

General or special purpose manipulator - depending on the target

Single manipulator

Use of standardized modules

Separate stabilization arms

Prepared worksite

CHAPTER 7 CONTROL SYSTEM TRADEOFFS

The most important control system tradeoff - manual vs. computer control, has already been discussed in Chapters 4 and 6. Based on the functional allocations for each mission and teleoperator system, the issues which remain to be resolved for development of man-machine interface requirements in control systems include:

- Definition of controllers
- Integration of manipulator control with free flyer control
- Control of visual system elements

1. Manipulator Controller - General

The two basic types of general purpose manipulator controls are rate control and position control. Rate control implies that the manipulator continue a commanded motion at a specified rate as long the control is applied. Rate control can be either fixed or variable. Variable control can be either selectable or proportional to the input. Position control implies a spatial relationship between the controller and the controlled element.

Rate control is usually provided by means of switch control on stick controller. A survey of 91 existing manipulators revealed that more than half (55%) are switch controlled. The majority of undersea manipulator applications use switch control. Very few of the existing systems use stick control.

Position control is generally implemented through a master-slave arrangement wherein the position of the controller (master) dictates the position of the end effector (slave). Basic types of position control include the exoskeleton controller, the replica controller, and the analog controller. This latter controller has been recommended by Martin Marietta for shuttle attached manipulator control (1971).

Few experimental studies have been conducted to compare performance on different types of manipulator controllers. One basic problem in performing such research is the diversity of manipulator systems, which are usually constructed for a specific application and therefore designed for the specific requirements of that mission. Existing manipulator systems vary widely in terms of reach, number of joints, load carrying capacity, stall torque, rate of motion, and force application capability. Attempts have been made to develop controller concepts for the generic group of anthropomorphic manipulators, those which more or less replicate the functional capability of the human arm. These manipulators, to be designated in this report as general purpose manipulators, can vary from three up to nine degrees of freedom and can lift from one-tenth to one and one-half times their own weight.

One study which reported performance data on switch controllers and stick controllers was performed by Pesch et al. of General Dynamics for the Office of Naval Research (1970). This study found a small but consistent superiority for pushbutton control over joystick control for underwater salvage operations. This superiority was noted both for time to perform and performance accuracy.

Bell Aerospace recently completed a study of free flyer requirements in a satellite servicing mission, for Marshall Space Flight Center (1972) Results of this study indicated that exoskeleton control was superior to analog control which was, in turn, superior to switch control.

Based on an in-house study, MSC personnel recently cited findings of a clear superiority for position control over rate control in terms of time to perform a maze tracking task with the shuttle attached manipulator. Results of this test have not yet been formally reported.

Before attempting to compare satellite retrieval and servicing requirements with controller capabilities, a better understanding is needed of the significant capabilities and limitations of alternate controller concepts. The concepts selected for analysis were:

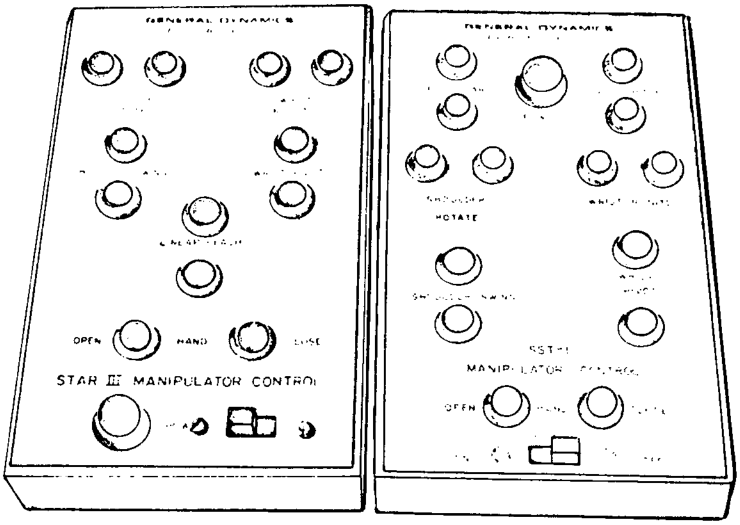
1. Discrete switch (switch box or keyboard)
2. Joystick with integrated function switches
3. Joystick pivoted in the middle to increase degrees of freedom
4. Joystick with separate mode switches
5. Isometric joystick (MIT)
6. Exoskeleton master controller (Rancho Los Amigos)
7. Mechanical analog master controller (Martin Marietta)

These controller concepts are described in greater detail in Tables 38 through 44. Each concept was evaluated on a series of criterion measures listed in Table 45. These criteria are classified into the following categories:

Controllability
Operability
Handling Qualities
Flexibility
Safety
Reliability/Maintainability
Physical Characteristics

TABLE 38

Concept 1 Discrete Switch



Types - Switch Box, Keyboard

Description - A number of toggle switches or pushbuttons for control of manipulator degrees of freedom

One switch controls 1 or 2 degrees of freedom

Type of control - Fixed rate

Degrees of freedom controlled - 1 or 2 via each switch

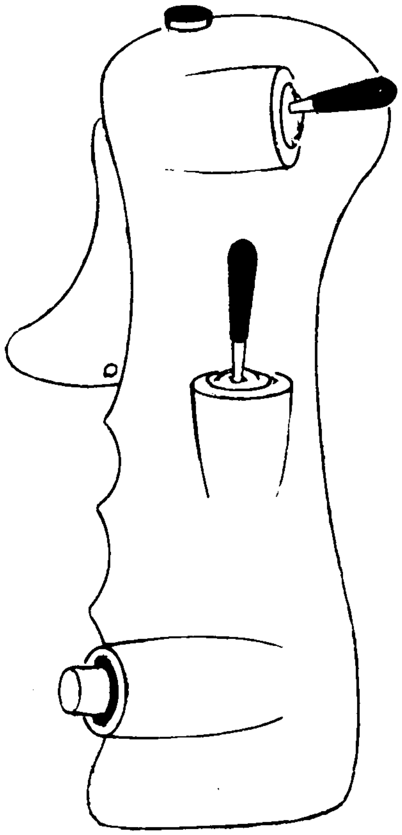
State of development - Used in several unilateral manipulator control systems for earth based operations (50% of the 60 manipulator systems identified in the report on Man vs. Manipulator, Saenger and Malone, 1970)

Implementations - Bell Aerosystems - switch box

- General Dynamics Underwater Manipulator Studies - switch box

TABLE 39

Concept 2 Joystick and Integrated Switches



Types - Sidearm controller, Pencil stick, T handle with function switches integrated into the stick

Description - Stick for controlling certain degrees of freedom with switches for controlling others and for controlling modes of operation, gains, and sensor activation

Type of control - Rate
- Proportional - where stick displacement is proportional to rate of change of controlled element
- Fixed - where a fixed constant rate is commanded

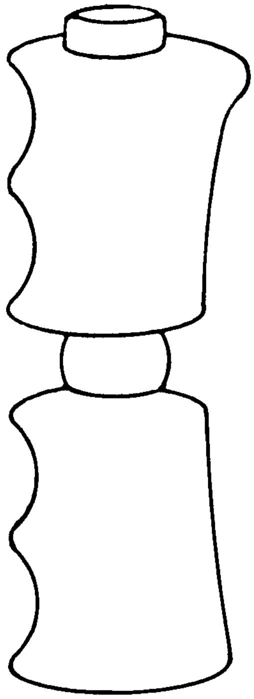
Degrees of freedom controlled - 4 in the stick, (fore-aft, left-right, twist, left-right, up-down)

State of development - Apollo, Gemini, High Performance Aircraft

Implementations - LTV Cherry Picker at MSFC

TABLE 40

Concept 3 Pivoted Stick



Types - Sidearm controller, Pencil stick

Description - Stick pivoted at the base and again at some point along the shaft. Requires an additional switch to select the portion of the stick to be activated

Type of control - Rate - proportional or fixed

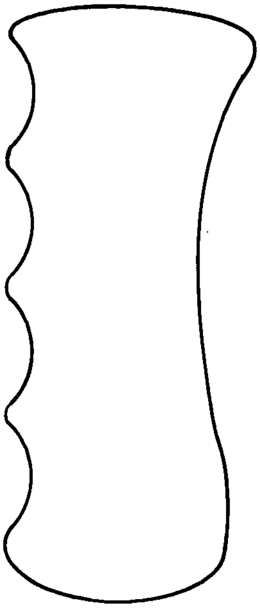
Degrees of freedom controlled - 7 (possibly 8)

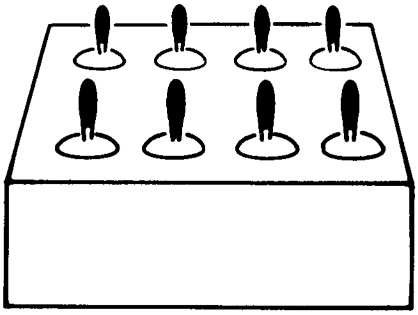
State of development - Undetermined

Implementation - None

TABLE 41

Concept 4 Joystick with Mode Switches





Types - Sidearm, Pencil stick, T handle

Description - Stick controls pitch, roll, yaw, and extension
Separate switches select joint to be controlled

Type of control - Rate - proportional or fixed

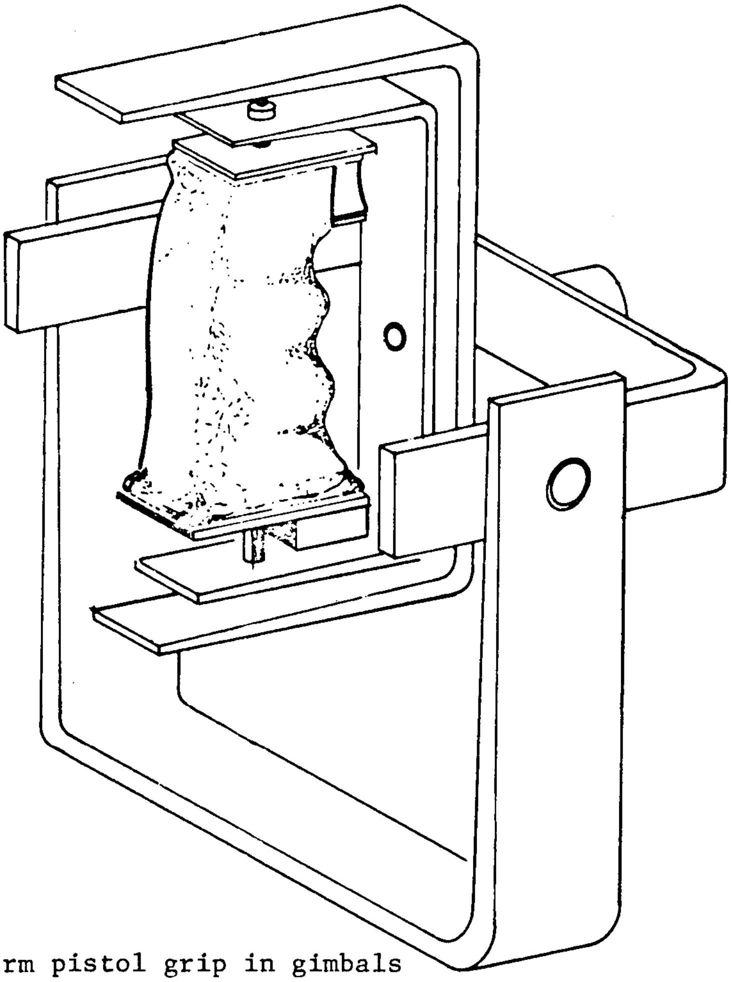
Degrees of freedom controlled - Up to 4 in each joint

State of development - The control concept for the North American Rockwell shuttle attached boom

Implementation - None

TABLE 42

Concept 5 MIT Isometric Controller



Type - Sidearm pistol grip in gimbals

Description - Stick which provides 3 degrees of freedom rotational control and 3 degrees of freedom translation control. Forces applied in the X, Y, and Z direction provide translation of the end effector along the right-left, fore-aft, and up-down axes respectively. Rotation about the gimbals provides turn, twist, and tilt of the effector.

Type of control - Rate control in that the effector continues moving as long as the stick is displaced linearly. Position in that position of the stick alters position of the effector (within small limits)

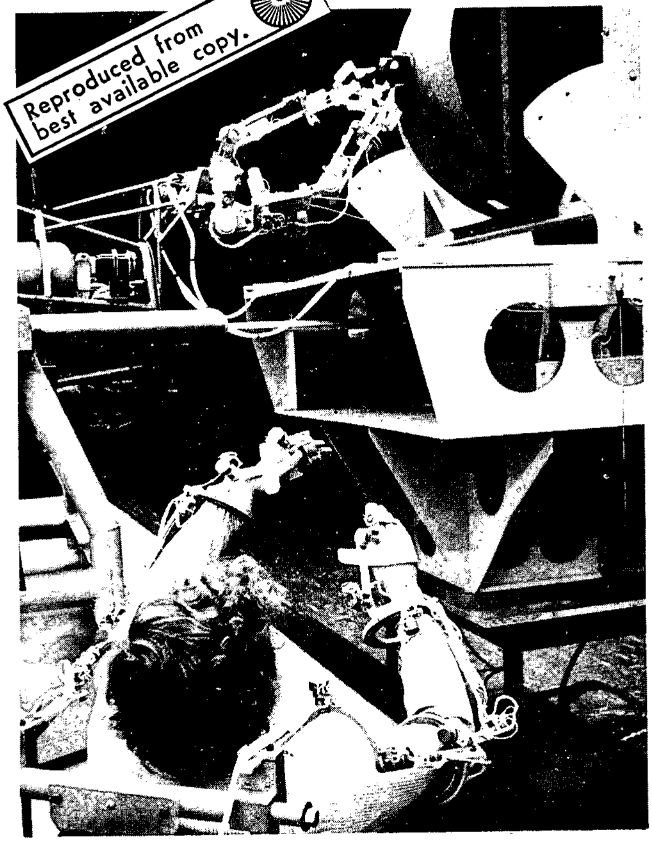
Degrees of freedom - 6

State of development - Prototype already available at MIT. Improved version being designed by Matrix Research Company

Implementation - MIT investigations

TABLE 43

Concept 6 Exoskeleton Master Controller



Courtesy of Bell Aerospace

Types - Full arm interface or hand interface only - Anthropomorphic configuration of master arms

Description - Master slave with the slave arm position reflecting the position and configuration of the master. In some cases, the control is worn by the operator, while in others only his hands are inserted into the master effector element

Type of control - Position for arm control, possibly rate for effector control

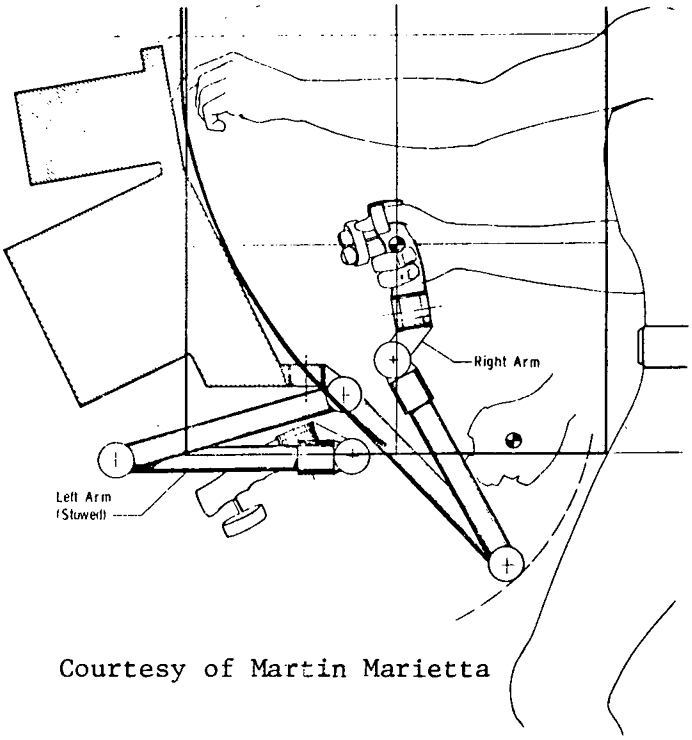
Degrees of freedom controlled - Up to 9

State of development - Well defined for earth applications. Also developed by GE (ADAMS), MBA, and El Rancho Los Amigos

Implementation - El Rancho at Bell
ADAMS at MSFC

TABLE 44

Concept 7 Mechanical Analog



Courtesy of Martin Marietta

Types - Manipulator replica, stick position control with switches

Description - Positioning of master stick or manipulator replica
in space positions slave arm

Type of control - Position through the stick/replica
Rate through the switches

Degrees of freedom - Unlimited

State of development - Two prototypes - from El Rancho
- Replica concept by MBA
- Attached manipulator control concept by Martin

Implementation - Bell and MSFC

TABLE 45

Controller Evaluation Criteria

Controllability

- High accuracy control of effector position/orientation
- High accuracy control of manipulator position/orientation
- High accuracy control of manipulator rate
- Capability of large rapid input
- Capability of simultaneous control of 2 arms
- Capability of simultaneous control of 2 or more degrees of freedom of a single arm
- Minimum number of controls and controllers
- Maximum integration with force feedback/contact sensors
- Ease of indexing manipulator/effector position (repeatability)
- Ease of indexing manipulator/effector rate
- Minimum time to initiate a control action
- Maximum number of degrees of freedom controllable
- Minimum miss distance
- Capability of tracking a moving target
- Immediate feedback of manipulator position-orientation
- Immediate feedback of manipulator rate-acceleration

Operability

- Minimum requirements for adjustment of the hand on the control or removal of the hand from the control
- Minimum likelihood of substitution errors (selection of wrong control)
- Minimum likelihood of adjustment errors (selection of wrong response on right control)
- Minimum likelihood of inadvertent actuation (accidental or non-intentional input)
- Minimum likelihood of sequential errors - performing operations out of sequence
- Minimum workload
- Minimum interference with display monitoring
- Minimum interference with operation of other controls (video system controls, sensor mode, etc.)
- Minimum number of discrete operations
- Minimum number of different operations associated with controlling different degrees of freedom
- Minimally constrained by limitations of the human arm/hand
- Minimum requirements for operator involvement in situations where moderate to long delays (waiting periods) are experienced
- Capability of enhancing visual depth/distance estimates
- Capability of operating in alternate modes
- Minimum operating volume/space required
- Capability of operating in computer assist mode
- Capability of extended reach

Minimum time to train operators
Minimum demands on operator memorization
Capability of applying minimum force/torque
Capability of force gradients over a wide range
Capability of multiple effector operations
Minimum impact on effector grip integrity
Capability of long duration holding by the effector

Handling Qualities

Minimum cross coupling
Maximum stability when stationary
Maximum stability when in motion
Capability of proportional input/output
Capability of non linear input/output
Maximum control sensitivity

Flexibility

Capability of sharing with other functions
Flexibility of adjusting rate/position inputs
Flexibility of modifying position/rate indexing

Safety

Minimum interference with emergency escape capability
Minimum hazards in manipulator failure mode
Capability of manipulator/effector emergency backoff
Minimum likelihood of collision with structures
Minimum likelihood of collision with other manipulator
Minimum electrical hazard to operator

Reliability/Maintainability

Feasibility of spares - redundant controller
Minimum maintenance requirements
Modular design
Maximum reliability/availability

Physical Characteristics

Minimum weight
Minimum power
Minimum stowed volume
Minimum mechanical interface
Minimum structural interfaces
Minimum electrical interfaces

The performance of each concept was derived by rating its expected effectiveness or capability on each criterion. This analysis is presented in Table 46. A summary of the ratings in each class and overall is presented in Table 47. As indicated in this table, four controller systems were selected for additional consideration: the integrated joystick/switch; the pivoted stick; the isometric stick; and the analog position controller. A summary of the significant advantages and disadvantages of each controller is presented in Table 48.

2. Manipulator Controller - Specific Requirements

In order to establish design requirements for manipulator control systems, an analysis was performed to identify the satellite retrieval and servicing tasks which require manipulator/effector control, and to establish requirements associated with each control task. These requirements include: frequency of control; estimated duration (using timeline data from the GE 1969 Ames study as a guide); complexity in terms of time criticality, difficulty or requirements for high attention control (close control); and accuracy limits on the control. These requirements are presented in Table 49 for the free flier performing satellite retrieval, in Table 50 for the attached teleoperator performing satellite retrieval, and in Table 51 for either free flier or attached performance of satellite servicing tasks.

For the free flier satellite retrieval, eight tasks were identified (from Table 22) which required manipulator control. The maximum estimated time to perform these tasks was 68 minutes. A total of 68% of the tasks (5 tasks) were rated high in terms of complexity, while 75% (6 tasks) require high accuracy.

For attached teleoperator satellite retrieval, 17 individual manipulator tasks were identified (from Table 24) which required from 92 to 167

TABLE 46

Evaluation of Controller Concepts

				Concepts			
	1	2	3	4	5	6	7
Criteria	Switch	Stick & Switch	Pivoted Stick	Stick & Mode Switches	Isometric Stick	Exoskeleton	Martin Analog
Controllability							
Effector Position	3	3	3	2	3	4	4
Manipulator position	1	1	1	1	3	4	4
Manipulator rate	1	4	4	3	2	3	3
Large rapid input	1	2	3	2	3	4	4
2 arm control (simul.)	1	2	3	2	3	4	4
2 d f control (simul.)	1	3	3	2	4	4	4
Minimum number controls	1	2	2	1	4	4	4
Force feedback	0	2	2	1	2	4	4
Position indexing	0	0	0	0	2	4	4
Rate indexing	0	3	3	3	2	1	2
Response time	1	3	3	2	2	4	4
d f controllable (max.)	4	3	3	4	3	2	3
Miss distance	1	2	3	2	3	4	4
Tracking	1	2	3	2	2	3	4
Feedback - position	0	1	1	1	2	4	4
Feedback - rate	1	4	4	3	2	2	3
SUM	17	37	41	31	42	55	59

Rating Scale

Value	
0	Minimal capability/poor performance
1	Limited capability - severe constraints
2	Moderate capability in some modes
3	Good capability - majority of applications and modes
4	Excellent capability

TABLE 46 - Continued

	Concepts						
	1	2	3	4	5	6	7
Operations	Switch	Stick & Switch	Pivoted Stick	Stick & Mode Switches	Isometric Stick	Exoskeleton	Analog
Hand adjust requirements	1	3	2	1	4	4	3
Substitution errors	1	2	2	2	4	4	4
Adjustment errors	2	3	3	2	3	4	4
Inadvertent actuation	1	2	3	2	3	1	2
Sequential errors	1	3	2	2	2	4	4
Workload	1	2	2	2	3	3	3
Display interference	3	4	4	4	4	1	1
Control interference	2	4	4	4	4	0	2
Discrete operations	0	2	2	2	4	4	4
Different operations	2	2	2	2	2	4	4
Human arm limitations	4	4	4	4	4	0	1
Long delay (wait)	3	4	4	4	4	1	3
Depth enhancement	0	2	2	2	2	4	4
Alternate modes	4	3	3	3	4	0	1
Training time	1	2	2	2	2	4	4
Operator memory	1	2	2	2	3	4	3
Minimum force	1	2	2	2	4	4	4
Force gradients	1	2	2	2	4	4	4
Multiple effector	4	3	3	3	3	2	2
Grip integrity	3	3	3	3	3	2	3
Long duration held	4	4	4	4	4	1	4
Operating volume	3	4	4	3	3	1	1
Computer assist	1	2	2	2	4	1	2
Capability of extended reach	4	4	4	4	4	1	1
SUM	48	68	67	63	81	58	68

TABLE 46 - Continued

	Concepts						
	1	2	3	4	5	6	7
	Switch	Stick & Switch	Pivoted Stick	Stick & Mode Switch	Isometric Stick	Exoskeleton	Analog
Handling Qualities							
Cross coupling	4	3	2	3	2	1	1
Stability - static	4	4	4	4	3	2	3
Stability - dynamic	1	4	4	4	4	3	3
Proportional input	1	4	4	4	4	3	4
Nonlinear input	1	4	4	4	4	2	3
Sensitivity	4	4	4	4	3	2	3
Flexibility							
Control sharing	4	4	4	4	3	0	1
Input adjustment	2	4	4	3	2	0	2
Indexing adjustment	1	3	3	3	2	1	2
Safety							
Escape	4	4	4	4	3	0	3
Hazards in failure mode	4	4	4	4	4	1	4
Backoff	2	3	2	2	2	4	4
Collision - structures	1	2	2	2	2	4	4
Collision - arm	1	3	3	3	2	4	4
Electrical hazards	3	3	3	3	2	1	2
Reliability/ Maintainability							
Spares	4	4	3	3	2	0	1
Minimum maintainability	4	3	2	2	2	0	0
Modular design	4	4	4	4	2	1	1
Maximum reliability	4	4	3	3	2	1	1
Physical							
Weight	4	3	2	3	2	0	1
Power	4	3	2	2	2	1	1
Volume	4	4	4	4	3	1	1
SUM	61	78	71	72	57	32	49

TABLE 47

SUMMARY OF RANKINGS

CONCEPTS

	1 Switches	2 Stick & Switch	3 Pivot Stick	4 Stick & Mode Switch	5 Isometric Stick	6 Exo-skeleton	7 Analog
Controllability	7	5	4	6	3	2	1
Operations	7	2	4	5	1	6	2
Handling	6	1	3	1	4	7	5
Flexibility	4	1	1	3	4	7	6
Safety	5	2	3	3	5	7	1
Reliability/ Maint.	1	2	3	3	5	7	6
Physical Characteristics	1	2	4	3	5	7	6
Overall Rank	7	1	3	5	2	6	4
Concepts selected for consideration		*	*		*		*

Table 48

Summary of Concept Advantages and Disadvantages

Switch Box

Advantages

No human arm limitations
Capable of controlling more than 2 arms
Capable of operating in alternate modes
Capable of multiple effector control
Capable of long duration object holding
Minimum cross coupling
Maximum stability and sensitivity
Amenable for control sharing
Minimum hazard
High reliability/maintainability
Low weight, power, volume

Disadvantages

Number of controls
No force feedback or position feedback
No indexing of position or rate
Large number of discrete operations - no integration

Joystick

Advantages

Rate control and rate feedback
Small input control
Control integration
Minimum control interference
Minimum limitations of the human arm
Good for long delay and long duration holding
Good for alternate mode and control sharing
Good handling qualities
Good flexibility
Good safety and reliability

Disadvantages

Cannot control more than 2 arms
Minimal position feedback

Table 48 - cont'd

Exoskeleton

Advantages

Capable of large rapid input and emergency backoff
Capable of 2 arm and 2 degrees of freedom simultaneous control
Minimum number of controls
Good force feedback and slip/grip sensor integration
Excellent position feedback
Minimum hand motion requirements (removal of hand from controller)
Minimum substitution and sequential errors
Minimum discrete and different operations
Good enhancement of visual depth cues
Minimum requirements for memorization
Minimum likelihood of collision

Disadvantages

Minimum rate indexing
Interferes with other controls and displays
Limited by the human arm
Cannot control more than 2 arms
Limited for long duration hold
Large operating volume
Poor cross coupling
Poor flexibility, safety and reliability/maintainability
Poor weight, power and stowed volume

Mechanical Analog

Advantages

Large rapid input and emergency backoff
Two arm simultaneous control
Good depth enhancement
Good long duration hold
Good proportional input
Small likelihood of collision

Disadvantages

Human arm limitations
Cannot control more than 2 arms
Cannot operate in alternate modes or share controls
Poor integration of grip/slip sensors
Poor operating volume
Poor cross coupling
Poor reliability, weight, power and stowed volume

Table 48 - cont'd

<u>Isometric Stick</u>

<u>Advantages</u>

- Capable of controlling two degrees of freedom simultaneously
- No human arm limitations
- Good operability
- Good extended reach
- Good stability
- Good control integration

<u>Disadvantages</u>

- Cross coupling
- Time to train
- Reliability/maintainability
- Poor indexing
- No force feedback

minutes. Of these tasks, 35% or 6 tasks were judged to be of high complexity while 77% (13 tasks) were rated high in accuracy required. A total of 30 satellite servicing tasks were identified which required 157 minutes. Of these, 10% (3 tasks) were rated high in complexity while 50% (15 tasks) were judged to require high accuracy.

The most complex manipulator control application is therefore free flier satellite retrieval while the application requiring the longest duration control sequence is attached satellite retrieval. Consideration should be given to the expanded use of automated and computer assisted techniques in these applications if reductions in complexity and duration are deem advisable. Satellite retrieval with either free flyer or attached manipulator required higher accuracy of control than did the satellite servicing mission.

Based on an analysis of these tasks (in Tables 49, 50, and 51), the elements of manipulator control can be identified as:

gross arm control - motion of entire arm or segments to move the effector over a relatively large distance

fine arm control - motion of entire arm or segments of the arm over short distance and/or with precision placement of the arm and effector

multi arm control - motion of two arms simultaneously

gross hand control- gross orientation or grasping

fine hand control - fine orientation or dexterous grip

tool attach control-emplacement of tool

tool positioning control - fine orientation and alignment of tool with respect to work surface

tool control - operation of tool

Gross arm control involves the moving of the entire arm or of segments of the arm. This control is best accomplished by mechanical analog and exoskeletal devices since it involves primarily control of position and simultaneous control of 2 or more degrees of freedom. Five of the eight free flier satellite retrieval tasks, seven of the 17 attached satellite retrieval tasks, and 13 of the 30 satellite servicing tasks require gross arm control. However, in satellite retrieval, several of the gross arm control tasks require tracking a moving target and relatively long duration holding of the target (during despin). The mechanical analog controller performs relatively poorly in tracking while the exoskeleton is poor for long duration target holding. In terms of time duration, 90% of free flier satellite retrieval manipulator control is spent in gross arm control while 60% of the time is spent on gross arm control in the attached retrieval mission and 50% in the satellite servicing mission. Based on these data, it is recommended that first consideration should be given to analog, isometric or joystick control for gross manipulator arm control.

Fine arm control involves precision placement of the arm and effector, usually requiring small motions to translate and adjust position and short duration control. While fine arm control is normally required at the termination of gross arm control motions, it has been identified as being required for two free flier satellite retrieval tasks, four attached retrieval tasks, and five satellite servicing tasks. Fine arm control entails such capabilities as high accuracy position control and position feedback, both of which indicate use of analog or exoskeletal devices. Fine control of arms, however, also requires small position input capability, control integration and stability of control, which indicate use of rate controllers.

Fine or gross effector control is required for one free flier retrieval task, four attached retrieval tasks, and 12 of the 30 satellite servicing tasks. Effector control involves 10% of the time for free flier retrieval manipulator tasks, 20% for attached retrieval and 48% for satellite servicing.

In selecting a mode of control for effector control, consideration must also be given to tool control. None of the manipulator tasks identified in either satellite retrieval mission require control of tools, while 4 satellite servicing tasks require tools, which tasks account for 30% of the time spent in satellite servicing. In addition, all satellite servicing tasks rated as high complexity involve tool operations. One of the more difficult tool operations performed with a manipulator is positioning of the tool such that it is perpendicular to the work surface. In a review of past research in manipulator control capability, Pesch et al (1970) at General Dynamics cited findings where errors in positioning a tool normal to a work surface were as great as 30° from the vertical. This operation requires a good representation of depth and good cues to judge the vertical and, as such, is more appropriately classified as a display rather than a control operation. However, it mush be considered in developing controller requirements. Due to its capability to perform small motions and adjustments with good position and orientation feedback, the position controller is probably superior to the rate controller for tool positioning.

Other effector operations include orientation of the effector and actual operation of the grip or tool. Effector orientation is best controlled via an analog device since the orientation of the effector has an effect on and is affected by the orientation of the arm in back of it. Effector operation, however, is best controlled by a rate controller due to requirements for small, precise motions and adjustments.

Based on these analyses, it is concluded that selection of a controller for each mission - system combination cannot be made based on existing data. Much additional research is required to develop the optimum controller for a specific application.

3. Integrated Manipulator Mobility Unit Control

In addition to manipulator control, control systems must be provided in the free flier for control of the vehicle itself. It is recommended that side arm translation and attitude controllers be incorporated into the control station for vehicle control. Control of the mobility unit in the attached system actually involved control of manipulators since the mobility unit is the 40 or 50 foot articulated boom. At the end of the boom is the end effector which is actually a manipulator system comparable in size and performance capability with the free flier manipulator system. For the attached system, then, control of two different types of manipulator systems will be required (the boom and the effector) each of which system can include two arms. For the free flier vehicle control and manipulator control is required. The next question is, can and should these control functions be combined or shared in a common controller?

For satellite servicing, when the mobility unit is assumed to be docked to the satellite, no simultaneous control of mobility and manipulation is required. In this mission, the controls can logically be shared. In satellite retrieval missions where capture of an uncooperative and dynamic satellite is involved, simultaneous control of the mobility unit and manipulator or capture device will be required. These control operations can be handled in at least one of three modes:

- single operator controlling both the mobility unit and manipulator simultaneously
- one operator controlling the mobility unit while another controls the manipulator
- control sharing between man and computer where the computer either controls attitude and position of the vehicle or synchronization, closure and capture operations of the arm/effector, and the man in each case controls the other function.

Single operator control is probably not feasible for the free flier application requiring manipulator control where, while CMG's can effectively hold attitude constant, continual translational commands are required to maintain position and change position as required. It is conceivable that a single operator could control translation with his left hand and switch his right hand from the vehicle attitude control to capture device control. However, the translation task alone imposes a heavy load on the man since he must continually sense rates in each of three axes and apply counter forces to null these rates. Adding the capture device control to this close control of vehicle position would impose too severe a workload on the operator. Single operator control is feasible if the grappler is not controllable except as a function of vehicle position. This corresponds to the docking operation where the operator must position an element of his own vehicle to spatially coincide with an element on the target.

Single operator control of the attached manipulator is more feasible since the boom will remain in a commanded position and orientation without constant adjustment. During final closure, the man may have to switch back and forth between boom and end manipulator control.

Dual operator control is a logical alternative to single man use but does present some difficulties. The simultaneous control of mobility and manipulator must be extremely well coordinated with demands to modify one of the two elements in quick time based on responses and changes in the other. Such highly integrated control is difficult to achieve with two operators. Dual operator control also requires additional internal shuttle space set aside for control panels and increases total training requirements as well as training requirements for each operator since each must be skilled in the functions performed by the other. Finally, dual control presents problems of control authority, areas of responsibility, interface and cooperation and should be avoided except where control operations are more or less independent.

Man-computer control sharing or use of computer assisted control offers the best alternative to reducing an excessive workload on the man. This alternative has the advantages of single operator control since, even while performing its assigned operations, the computer itself is under complete control of the man. All integration of information is being done by and under the direction of one man. All decisions are made by one man. Implementation of this alternative does increase system complexity, however, and additional analysis and research are required to justify its use and to establish the levels and types of computer control.

The recommended concept for teleoperator control, therefore, incorporates some level of computer control (more in the attached satellite retrieval mission, moderate in free flier retrieval and minimal in satellite servicing) ranging from computer assisted, through supervisory to automatic control.

4. Control of Video Systems

There exists today an increasing interest in developing video control systems which ensure that the operator need not remove his hands from the controller to modify video parameters. Consideration is being given to head aimed and eye position control of video field of view and direction of view. Such concepts are a logical outgrowth of the use of exoskeletal controllers where the operator's hands are in fact slaved to the master controller which controls the position of the slave effector. Their application in satellite retrieval and servicing missions is at present unclear.

In free flyer satellite retrieval the operator will face minimal requirements to alter his direction of view independently of alterations in the vehicle's docking axis alignment. An adequate field of view should be sufficient for this mission. In attached manipulator satellite retrieval modifications of direction and/or field of view may be required. However, with two arms in use, if the manipulator holds its last commanded position, if the controller remains stationary in a hands-off condition, and if time to perform is not critical, the operator can adjust his video by removing his hand from the controller and manually controlling the video parameters. If only one boom is being used the operator has a free hand to control video. The same reasoning applies to satellite servicing, with either a free flier or an attached manipulator.

In summary, it can be concluded that manual control of video parameters is practical and that the additional complexity associated with head aimed or eye controlled TV is unwarranted.

5. Summary

To sum up, it is not possible at this time to designate one type of controller as being optimal for a satellite retrieval or satellite servicing mission using either a free flyer or an attached manipulator. Opinions of personnel engaged in developing teleoperator system technology vary widely concerning the relative effectiveness of alternate controller configurations. What little empirical evidence is available is of questionable validity and is contradictory. Based on available data the only conclusions which can be drawn concerning controller effectiveness is that switch type control should be dropped from further consideration due to workload and accuracy problems.

Work is progressing at MIT on an advanced controller concept which could incorporate the advantages of rate and position control without the significant disadvantages of each. This concept is also being investigated by Matrix Research for MSFC. Additional research and technology development in controller design and performance for retrieval and servicing missions is required. Work is underway at MSFC and at MCS to provide the needed answers. Work has also been progressing at Ames Research Center to develop a manipulator controller as an application of the hard suit technology developed at that center. While this approach represents a considerable advancement in the exoskeletal controller technology, it is still an exoskeleton type of controller and therefore suffers from the drawbacks noted for that class of controller concepts.

Additional research is also required on the effective integration of manipulator control and mobility unit control. This research must also consider alternate approaches to manual control of both elements when such control is required simultaneously.

The question of video control is also unanswered based on existing data. What is needed here is a careful analysis of the requirements for video control which will serve as the basis for concept development. It seems that the current attention being given to head aimed and eye controlled video is unwarranted in terms of available information concerning video control requirements and their relationships with manipulator or mobility unit control.

C. 2

TABLE 49

Free Flier System Satellite Retrieval Tasks Requiring Manipulator Control and Requirements Associated with Control

Task	Control	Frequency	Duration (minutes)	Complexity	Accuracy
Orient manipulators for capture	. gross control for deployment . fine control for alignment	one time one time	1 - 2 2 - 5	Low Moderate - depending on satellite dynamics	Moderate High
Synchronize rates	. computer control or . man control of device rotation	one time	5 - 10	High - requires full attention while controlling vehicle attitude	High .1 to 2 RPM
Commence final closing	. arm extension and/or vehicle approach	one time	up to 10 min.	High - simultaneous control of manipulator and mobility unit	High Rates .05 to .2 fps
Maintain alignment	. fine arm position control	one time	continuous during closing	High - same as above	High
Secure effector at contact	. fine grip control	one time	less than 1	High - tracking of attach point and effector - possibly in more than 1 plane	High Full firm grasp
Despin	. gross arm control	one time	up to 10	High - maintain control while monitoring forces, rates and stability and being prepared to take quick release action or modify force application	High Remove all rotational rates ± TBD
Prepare for recovery	. gross arm control	one time	up to 10	Moderate - positioning of effectors for recovery	Moderate
Prepare satellite	. gross arm control	one time	up to 20	Moderate - remove appendages, purge expendables	Moderate

TABLE 50

Attached System Satellite Retrieval Tasks Requiring Manipulator Control and Requirements Associated with Control

Task	Control	Frequency	Duration (minutes)	Complexity	Accuracy
Command closing velocity	Supervisory - man input, computer control	one time	20 - 30	Low	High .4 fps ± .1 fps
Maintain orientation and perform corrections	Supervisory - manual override	continuous during approach	2 - 3 min.	Moderate	High
Command braking	Supervisory	one time	less than 1	Low	Moderate Stop in 1.5 ft. command at 12 ft. ± 2 ft. range
Assume station keep position	. Supervisory . Computer assisted	one time	less than 1	Low	Moderate Range of 10 ft. ± 2 ft.
Maneuver around satellite	. Computer assisted	continuous	up to 5	High - maintain 10 ft. separation	Moderate
Align docking axis	. Computer assisted	one time	up to 2	High	High
Position for capture	. Fine arm position control	one time	1 - 2	Moderate	High
Orient effectors	. Fine effector control	one time	1 - 2	Moderate	High
Synch. rates	. Computer	one time	5 - 10	Moderate	High .1 to 2 RPM
Final closing	. Fine manipulator arm control	continuous	5 - 10	High - control while monitoring rates and video	High .05 to .2 fps
Achieve contact and secure effector	. Fine effector control	one time	less than 1	High - track effector and attach point	High Full firm grasp

TABLE 50 - cont'd

Task	Control	Frequency	Duration (minutes)	Complexity	Accuracy
Despin	. gross effector - arm control or computer control	continuous	10 - 20	High - maintain control - vary force/torque over time	High
Prepare for recovery	. gross effector control	continuous	5 - 10	Moderate - no demanding time constraints	Moderate
Impart closing velocity	. supervisory or computer assisted or computer control . multi arm control	continuous	20 - 30	Moderate - no demanding time constraints Moderate workload	High .174 fps ± .05
Brake	. Same as above fine control	one time	5 - 10	Moderate	High Begin at 25 ft. ± 1 ft.
Maneuver to recovery	. Same as above gross control	continuous	5 - 10	Moderate - high vigilance required	High
Emplace satellite	. Same as above fine control	continuous	10 - 20	High - tight clearance envelope for RAM and HEAO	High

TABLE 51

Satellite Servicing Tasks Requiring Manipulator Control and Requirements Associated with Control

Task	Control	Frequency	Duration (minutes)	Complexity	Accuracy
Ingress worksite	. gross arm control	once/site	2 - 5	varies with clearance and obstacles. probably moderate - not time constrained	Moderate
Stabilize mobility unit	. gross arm control	once	1 - 3	varies with stabilization requirements - not time constrained - probably moderate	Moderate
Orient manipulation for removal of module	. gross arm control	once	2 - 5	probably low	High
Configure worksite	. gross arm/tool control . tool positioning	once	5 - 10	probably moderate no real difficulty in control - bigger display problem	Moderate
Configure manipulation	. fine arm control . tool attachment	several - varying with number of tools	2 - 5	probably moderate - not time constrained. not difficult given adequate tool interface	Moderate
Uncover module	. gross arm control	once/ removal	2 - 5	moderate - gross motions not time constrained	Moderate
Stow Cover	. gross arm control	once/ removal	2 - 5	moderate given adequate stow device design	Moderate
Remove obstructions	. gross arm control . tool positioning . tool control	varies with number of obstructions	5 - 10	moderate to high depending on precision control of tools required	High Removal of all obstructions

TABLE 51 - cont'd

Task	Control	Frequency	Duration (minutes)	Complexity	Accuracy
Attach tether	. dexterous hand control . hand orientation control	once/ removal	2 - 5	Low to moderate depending on attachment device design	High - must connect
Break connections	. fine, dexterous hand control . tool positioning . tool control	varies with number of connections	10 - 20	Probably high - varies with number, type, clearance, visibility, accessibility, type motions required, number and type of tools, constraints on tool positioning.	High All connections broken
Stow connections	. gross hand control	same as above	2 - 5	Probably low	Moderate
Break lock	. fine hand control	once/ module	1 - 3	Moderate depending on lock design and accessibility	High On-off
Contact module	. fine dexterous hand control	once/ module	less than 1	Low - depending on hand orientation constraints	High Grip integrity
Free module	. fine dexterous hand control	once/ module	less than 1	Low	
Remove module	. hand orientation control . fine arm control	once/ module	1 - 3	Moderate - depending on rails or guide systems	High Removal complete
Handle module	. gross arm control . gross hand orientation	once/ module	2 - 5	Moderate - no time constraints and minimal limits on module transfer	Moderate
Stow module	. gross arm control	once/ module	2 - 5	Low depending on stow device design and location	Moderate
Detach tether	. fine hand control	once	less than 1	Low	High

TABLE 51 - cont'd

Task	Control	Frequency	Duration (minutes)	Complexity	Accuracy
Attach tether to fresh module	. fine hand control	once	2 - 5	Low to moderate	High
Retrieve fresh module	. gross arm control	once	2 - 5	Low to moderate depending on special handling requirements and clearances	Moderate
Inspect module	. gross arm control . dual arm coordination	once	2 - 5	Moderate depending on module size, mass	High
Orient module	. gross arm control	once	1 - 3	Low to moderate	High
Align module	. fine arm control . fine hand orientation	once	1 - 3	Moderate to high depending on clearances	High
Install module	. fine arm control	once	1 - 3	Moderate depending on clearances and aids	High
Adjust module	. fine arm control	several	1 - 3	Moderate	High
Make hold down	. fine hand control	once	1 - 3	Moderate depending on lock design	High
Unstow and make connections	. fine hand control . tool control	varies with number	10 - 20	High depending on number, type, clearances	Moderate
Detach tether Verify seating Retrieve cover	. gross arm control	once	5 - 10	Low	Moderate

CHAPTER 8 VISUAL SYSTEM TRADEOFFS

The visual system of a teleoperator system consists of:

Video sensor

Telecommunications

Image processing

Display and display visual aids

Lighting

Target satellite interface

The human operator

The essential component in the subsystem is the human operator. The primary interface between the operator and the world in which he is operating is the display subsystem. Therefore, characteristics of sensors, image processing, telecommunications, lighting and target interface subsystems will be considered only to the extent that they affect the display of information. Display and display visual aid characteristics will receive full treatment since these characteristics directly impact the quality and quantity of information presented to the operator. The operator component was analyzed in terms of the extent to which requirements placed on his visual system (as mediated by other subsystems) are within the capabilities of that system.

The first effort was directed toward establishing the mission operations which place requirements on the visual system. Table 52 presents a representative listing of visual system operations for associated rendezvous docking and satellite capture mission operations. Table 53 presents visual system operations for the satellite servicing mission operations.

Once an agreed on listing of visual operations was developed, an identification was made of the specific human visual perception requirements associated with each operation. For each perception requirement with each visual operation, the factors which affect performance of the operation

TABLE 52

Human Visual Operations for a Typical Remote Manipulator Rendezvous, Docking and Satellite Capture

Mission Operation	Visual Operation
Search for satellite	Discern the search field
Acquire the satellite	Distinguish the satellite as different from surrounding stars
Rendezvous with the satellite	Estimate range to go
	Estimate closing velocity
	Estimate line of sight rates
Station keep with the satellite	Same as rendezvous
Determine rotational parameters	Estimate rotational axis
	Estimate stability about the axis
	Estimate rotation rate
Align attitude	Estimate direction and degree of misalignments in pitch and yaw
Align inertial axis	Estimate alignment of x axis with satellite axis of interest
Inspect the satellite	Discern anomalies, deformations, etc.
Identify docking points	Discern points of interest
	Track these points
Accomplish final closure	Estimate alignments
	Estimate distance and rates
Detect obstacles	Discern and track potention obstructions
Achieve docking	Discern minimum range
	Discern rates at docking

TABLE 53

Human Visual Operations for Remote Manipulator Satellite Servicing

Mission Operation	Visual Operations
Identify components	Recognize patterns and forms
Access component location	Estimate distance - depth Estimate rate of arm/hand motion
Release/secure latches or locks	Identify latches, etc. Estimate clearances Verify - latch disengaged
Connect/disconnect leads, connections	Discern small leads Identify connection points Verify connectors made or broken
Remove component	Estimate clearances Estimate distances - depth Discern obstructions View entire housing
Repair component	View of component, tools and repair materials View of area to be repaired View of tool - material application Verification of operation
Align - adjust component	View alignment aid View alignment operation Estimate offsets, distances
Replace component	View of component while moved into position Alignment of component into housing View of entire opening View of component as it is emplaced/ installed
Inspect components	Pattern - form recognition Fault detection View from different aspects
Deploy structures	View of entire area View of obstructions View of deployment devices Estimate rate of motion Maintain spatial orientation

which are inherent in the operator, target and background, were identified as in Table 54.

The next step was to delineate the factors associated with subsystems other than the human operator which also affect performance of a visual operation. Factors or parameters for each subsystem were developed which included those itemized in Table 55. The relationships between the visual system subsystem parameters and the visual perception factors are indicated in Table 56.

An initial set of display design requirements was developed for selected parameters from Table 55 using system requirements developed in Chapter 3. These requirements are presented in Table 57 for the satellite retrieval mission and Table 58 for the satellite servicing mission. A total of 28 satellite retrieval tasks were identified which are considered important for design of the display system and 32 display tasks were identified for the satellite servicing mission. Table 59 presents recommended values for display parameters from other sources.

1. Size Resolution

The parameter of size resolution was considered important for approximately half of the retrieval tasks and about two-thirds of the servicing tasks. For retrieval, resolution requirements ranged from 5 arc minutes to 5 degrees while for servicing the range was 8 arc minutes to 2.4°. A review of other sources indicates that Bell recommends a resolution capability of 23 arc minutes while GE (1969) cites 5.8 arc minutes as being required. Based on these data, it can be concluded that the minimum size resolution should be 5 arc minutes, which approaches the threshold for human operators viewing a television monitor.

Size resolution, or number of TV lines, has a primary effect on observer

TABLE 54

Visual Perception Requirements and Factors

		Factors Influencing Performance		
Visual Operation	Visual Perception Requirements	Operator	Target Factors	Background
Discern search field	Pattern discrimination			Star density Star magnitude
Distinguish the target	Target detection	Size acuity Vigilance Search mode Location in field	Size Brightness Motion Time in field Target condition	Star brightness
Estimate range	Distance perception	Training acuity	Distance Size Motion	
Estimate closing velocity	Perception of size changes	Size discrimination	Size changes	
Estimate line of sight rates	Perception of motion	Adaptation Motion acuity Displacement acuity	Speed Direction Type motion Brightness Target condition Time in view Shape-form Contrast	Contrast
Estimate rotational axis	Perception of motion	Motion acuity Displacement acuity	Rotational rate Stability about axis Size Brightness	
Estimate stability about the axis	Perception of motion	Motion acuity Displacement acuity	Extent of variations Rate of variations Uniformity of variations	

TABLE 54 - cont'd

Visual Perception Requirements and Factors

Visual Operation	Visual Perception Requirements	Factors Influencing Performance Operator	 Target Factors	 Background
Estimate rotational rate	Perception of motion	Motion acuity	Rotational rate Uniformity of rate Uniformity of stability	
Identify attitude misalignments	Perception of form	Training Displacement acuity Form recognition	Stability Size Motion Reflectivity Surface uniformity	Sun angles
Discern structural anomalies and points of interest	Target detection Perception of form Pattern recognition	Training Size acuity Brightness discrimination Form recognition	Brightness Size Motion Contrast	Skin reflectivity Surface uniformity Motions
Track points of interest and obstacles	Perception of motion	Motion acuity	Size Motion Time in field Contrast	Brightness Surface uniformity Motions
Estimate alignments	Perception of displacement	Displacement acuity	Offset Size Motions Brightness Contrast	
Identify clearances	Perception of form	Acuity Pattern recognition	Contrast	Brightness
View of tools, materials	Eye - hand coordination	Depth and Distance Acuity Motion perception	Orientation Size Motion Contrast	Brightness

TABLE 55

Visual System Subsystem Parameters

Sensor

- Field of view
- Direction of view
- Depth of view
- Light response
- Motion resolution
- Size resolution
- Magnification/minification
- Rate of sweep
- Number of cameras
- Sensitivity to glare
- Type of lenses

Communications

- Signal Format - Analog or Digital
- Bit rate
- Signal/noise ratio
- Delay

Image Processing

- Image enhancement
- Noise reduction
- Interference compensation
- Rectification
- Generation of graphics

TABLE 55 - cont'd

Visual System Subsystem Parameters

Display

- Resolution of size
- Resolution of motion
- Contrast
- Color
- Symbology and scaling
- Frame rate
- Brightness
- Depth of view
- Tube size
- Number of tubes
- Tube persistence
- Distortion tolerances
- Ambient illumination

Display Aids

- Type
- Size
- Arrangement
- Duration
- Scaling
- Line resolution
- Symbology

TABLE 55- cont'd

Visual System Subsystem Parameters

Target Illumination

- Brightness
- Number of lights
- Area coverage
- Direction
- Spectral response

Satellite interface

- Beacon light
  - number
  - configuration
  - condition
  - brightness
  - repetition rate
  - on-off cycle
  - spectral response
- Docking-alignment aid
  - type
  - size
  - color
  - contrast
  - shape

TABLE 56

RELATIONSHIPS BETWEEN VISUAL SYSTEM SUBSYSTEM PARAMETERS AND VISUAL PERCEPTION FACTORS

Visual System Subsystem Parameters	Visual Perception Factors Affected						
	Size Acuity	Motion Acuity	Size Descrim.	Form Percep.	Pattern Recog.	Depth Percept.	Bright Descrim.
Sensor							
Field of view	X	X	X	X	X		
Direction of view	X	X	X	X	X		
Communication							
Bandwidth	X	X	X	X	X		X
Signal Format	X		X	X	X		
Bit Rate	X	X	X	X	X	X	X
S/N Ratio	X	X	X	X	X	X	X
Signal Delay		X					
Display							
Size Resolution	X	X	X	X	X	X	
Motion Resolution		X					
Contrast	X	X	X	X	X	X	X
Color	X		X	X	X		X
Frame Rate		X					
Brightness							X
Depth of View			X			X	
Monitor Size	X	X	X	X	X	X	
Number of Monitors			X			X	
Ambient Illumination							X
Display Aids	X	X	X	X	X	X	X
Target Illumination	X	X	X	X	X	X	X
Satellite Interface	X	X	X	X	X	X	X

TABLE 57

Display Requirements - Satellite Retrieval

Display Task	Resolution		Field of View	Frame Rate	Brightness	Depth of View	Display Aids	Satellite Aids	Lighting
	Size	Motion							
Maintain surveillance attitude	.5°	-	60°	-	50 ft. L	-	. cursor . envelope display . geometry display	. beacon	-
Monitor range	Size changes of 1.6°		-	-	100 ft. L	-	. range aids . reticle	. beacon . strobe lights	-
Monitor range rate	-	30 arc min/sec	-	Moderate	100 ft. L	-	. range aids	-	-
Monitor LOS rates	-	18 arc min/sec for .1 fps rate at 20 ft.	-	Moderate	100 ft. L	-	. range aids	. beacon	-
Assume station keeping position	-	18 arc min/sec	-	High	100 ft. L	-	. range aids	-	-
Align altitude angles	3° off-set	-	-	-	100 ft. L	-	alignment aids	alignment aids	30° cone 50,000 ft. c for 100 ft. L at 20 ft.
Monitor obstacle location	15 arc min.	-	60°	-	100 ft. L	-	-	-	same as above
Maneuver around satellite	size changes of 2°	18 arc min/sec	60°	Moderate	100 ft. L	-	-	-	Directed

TABLE 57 - cont'd

Display Task	Resolution Size	Resolution Motion	Field of View	Frame Rate	Brightness	Depth of View	Display Aids	Satellite Aids	Lighting
Inspect satellite	5 arc min	-	to 15° with 4X Zoom	High	100 ft. L	-	Aided inspection routine	-	50,000 ftc 15° cone
Track satellite		1 rad/sec - RAM	60°	Moderate	100 ft. L	±3 ft. wobble of RAM at 20 ft. about 1° stereo acuity	-	-	Same as above
Identify axis of rotation		5°/sec	60°	Moderate	100 ft. L	±3 ft. wobble	Tracking aids	Markings	Same as above
Align docking axes	TBD	-	60°	-	100 ft. L	-	Align aids	Align aids	50,000 ft c
Measure rotational rates	-	30 arc min/sec for 1 rad/sec rate and accuracy of .1 RPM	60°	High	100 ft. L	-	Measure aids	Markings	Same as above
Measure stability about axis	TBD	TBD	60°	High	100 ft. L	TBD	TBD	TBD	Same as above
Identify attach points	14 arc min for 1 inch point at 20 ft.	-	-	-	100 ft. L	-	-	-	Same

TABLE 57 - cont'd

Display Task	Resolution		Field of View	Frame Rate	Bright.	Depth of View	Display Aids	Satellite Aids	Lighting
	Size	Motion							
Track points	-	3 rad/ sec OSO	60°	High	100 ft. L	1° stereo acuity	-	Markings	Same
Synchronize rates	-	2×10^{-4} RPM unaided .1 RPM required (ATS-V)	-	High	100 ft. L	-	Synch. aids non-visual	TBD	Same
Final Closing	-	Min. rate .05 fps Max. of .2 fps 25 arc min/ sec growth of target with .2 fps rate	15 ft. RAM end 37° - 20 ft. 87° - 1 ft.	High	100 ft. L	Stereo acuity 15 arc min at 5 ft for 6 inch offset	Ranging	Ranging	Same
Maintain Alignment	Detect .2 ft. offset 5° at 20 ft.	Track rotating points 5°/sec	45°	High	100 ft. L	-	Ranging Alignment	Ranging	Same
Achieve Contact	-	Detect deceleration .2 fps to 0 fps	-	High	100 ft. L	Stereo acuity 44 arc min at 5 ft for 3 inch offset	Ranging	Ranging	Same
Secure effector	1 inch at 5 ft. 5 arc min	-	22° for 2 ft. area at 5 ft.	Low	100 ft. L	44 arc min	-	Markings	3000 ftc for 100 ft. L at 5 ft.

TABLE 57 - cont'd

Display Task	Resolution		Field of View	Frame Rate	Bright.	Depth of View	Display Aids	Satellite Aids	Lighting
	Size	Motion							
Monitor rates	-	Track rotation rates .1 rad/sec (1 RPM) up to 3 rad/sec (30 RPM) Wobble angles 1° to 66° rate of 5°/sec	66° for wobbling RAM	High	100 ft. L	-	-	Markings	Same
Despin	-	-	66° max	High	100 ft. L	44 arc min	-	Markings	Same
Monitor rate reduction	-	Reduction from 30 RPM to 0 in 2 sec. Reduction of 66° wobble 5°/sec rate in TBD sec	66° max	High	100 ft. L	44 arc min		Markings	Same
Monitor stability	5 inch offset at 5 ft. (3°)	-	-	-	100 ft. L	44 arc min	-	Markings	Same
Verify despin completion	-	Wobble 0° ± .1° - ± .1 inch Rotation rate 0 ± .1 RPM	20°	High	100 ft. L	5 arc min for ± 1 inch offset at 5 ft. viewing distance	Rotation detection aids	Markings	Same

TABLE 57 - cont'd

Display Task	Resolution Size	Resolution Motion	Field of View	Frame Rate	Bright.	Depth of View	Display Aids	Satellite Aids	Lighting
Position for recovery	-	-	20°	Low	100 ft. L	-	-	Markings	Same
Monitor range/ rate	Null at 100 ft. ±2 ft. Null at 20 ft. ±1 ft.	.5 fps at 20 ft. - free flier .2 fps at 20 ft. - attached	45° 20 ft. area at 20 ft.	High	-	-	-	Shuttle aids	-

TABLE 58

Display Requirements - Satellite Servicing

	Resolution								
Task	Size	Motion	Field of View	Frame Rate	Bright.	Depth	Display Aids	Satellite Aids	Lighting
Search	Markings 1 inch at 24 inch 2.4°	-	3 ft. surface at 2 ft. about 60°	Mod.	>100 ft. L	-	Aided search	Markings	500 ftc for 100 ft. L at 2 ft.
Locate module	Identif. markings .1 inch at 24 inch 14 arc min	-	Small	Mod.	>100 ft. L	-	-	Markings	Same as above
Ingress work-site	Obstacles 1 inch at 24 inch	-	60°	Mod.	>100 ft. L	Gross	-	Markings	Same
Inspect site	Objects .1 inch at 24 inch 14 arc min.	-	60°	Mod.	>100 ft. L	Gross	-	Markings	500 ftc 2 locations
Orient for removal	-	-	60°	Mod.	>100 ft. L	Gross	-	-	Same
Configure site	-	Track gross arm rates .5 fps about 1°/sec	60°	High	>100 ft. L	.2 inch offset effector from object at 24" 3 arc min.	-	Markings	Same
Uncover module and stow	-	Same as above	Small	High	>100 ft. L	Same as above	-	Markings	Same
Remove obstructions	-	Same as above	Small	High	>100 ft. L	Same as above	-	Markings	Same

TABLE 58 - cont'd

Task	Resolution Size	Resolution Motion	Field of View	Frame Rate	Bright.	Depth	Display Aids	Satellite Aids	Lighting
Inspect module	8 arc min. .1 inch at 44 inch maximum off-set for 3 ft. surface	-	Small	Mod.	>100 ft. L	-	-	Markings	Same
Attach tether	14 arc min.	Track hand at .2 fps 25 min/sec	Small	Mod.	>100 ft. L	3 arc min.	-	Markings	Same
Break connection	8 arc min.	25 min/sec	Small	High	>100 ft. L	3 arc min.	Coding color	Markings High contrast leads	Same
Stow connection	14 arc min.	1°/sec	Large	Mod.	>100 ft. L	3 arc min.	-	Markings	Same
Break lock	8 arc min.	25 min/sec	Small	Mod.	>100 ft. L	3 arc min.	-	Markings Indicator	Same
Contact module	14 arc min.	8 arc min/sec	Small	High	>100 ft. L	3 arc min.	-	High contact handle	Same
Remove module	Offsets of 8 arc min.	.5 fps fore-aft plane rate of change of 2 arc min/sec at 2 ft.	Small	High	>100 ft. L	Approx. 1.5° for .5 ft. displacement	-	Alignment aids	Same
Handle module	-	25 min/sec	Large	High	>100 ft. L	-	-	-	Same
Stow module	-	25 min/sec	Large	High	>100 ft. L	About 1.5°	-	-	Same
Remaining tasks - reverse of above tasks									

TABLE 59

Teleoperator Display Requirements From Other Sources

	Number of Views	Field of View	Size Resolution	Motion Resolution	Frame Rate	Depth	Lighting
Bell Free Flier	2	30-45° 5-30°	23 arc min.	-	30	Dual Mono	13,000 ftc 130 ft. L at 10 ft.
GE Free Flier	3	2 - 10-60° 1 - 25°	5.8 arc min.	-	10	Stereo 0 to 400 ft. Mono when docked	155 ft. L
Martin Attached	4 (1 each arm 1 forward bay 1 rear bay)	-	300 line	-	20	Mono (?)	-
MBA Attached	?	60° full 6° foveal Dual field	1000 line system	-		Stereo foveal Mono peripheal	-
NR Attached	6 (1 each arm 3 in bay 1 along dock axis)	-	-	-	-	Mono	-

size acuity, or the smallest object perceptable to the observer. In specifying this effect, however, it is important to consider interactions between resolution of the display and other visual system parameters, notably field of view, telecommunications characteristics, contrast or gray scale, and monitor size. To this list must also be added target to camera distance and observer to monitor viewing distance.

Size resolution can be expressed in terms of visual angle subtended at the eye or in terms of number of TV lines included in the target image on the monitor. The visual angle is a function of the physical size of the image on the monitor and the viewing distance. The number of lines included is a function of monitor size, number of lines per frame, and field of view. A direct relationship between number of lines and angular subtense in arc minutes has been demonstrated by Hemingway and Erickson (1969) who reported that, as expected, the angular subtense bears an inverse relationship with the number of lines required for object detection. Moreover, these investigators reported that for angular subtenses between 6 and 16 arc minutes and for a 95% probability of signal detection, the functional relationship can be expressed as SA=90, where S is the number of lines per symbol and A is the angular subtense in minutes of arc.

An angular subtense of 5 arc minutes at a 20 inch viewing distance represents an image size of about .03 inches on the monitor. The lower limit of number of lines required for target detection is usually set at 2 lines. If the .03 inch image includes 2 TV lines, a tube size is required such that one inch includes 67 lines. For a 10 inch vertical dimension, this would require 670 active lines. In order to accomodate the 495 active lines for a standard 525 line system, the vertical dimension of the monitor must be of the order of 7 inches, which, with a 4 to 3 format, would require a monitor of about 11 inches diagonally.

The field of view and camera-target distance dictate the actual size of the object which includes .03 inches on the monitor. The minimum object sizes detectable for different field of view - distance combinations with a .03 inch spot size on a 7 vertical inch monitor are presented in Table 60.

TABLE 60

Minimum Object Size (in inches) Detectable
For Field of View and Distance Combinations

	Field of View			
Viewing Distance	10°	20°	30°	60°
10 feet	.10	.19	.30	.60
20 feet	.18	.37	.60	1.13
100 feet	1.00	1.87	3.00	6.00

The upper limit of field of view is dictated by the minimum size requirement for detection. The lower limit is fixed by the dimensions of the view required to perform the task. GE (1971) reported a requirement for a free flyer visual system to be capable of detecting a .25 inch wobble in a satellite at 5 feet distance. Again, with a .03 inch image on the 7 inch tube, this capability is provided with a field of view no greater than 44°. The minimum object sizes associated with a field of view of 44° at 10, 20, and 100 feet are .5, .98, and 5 inches respectively. If provided with pan and tilt capability, a maximum field of 44° is sufficient for satellite servicing given that the worksite area to be seen does not exceed the camera to surface distance.

The majority of studies concerned with field of view requirements for teleoperator systems usually noted a need for two fields of view, a wide field for close in work and a narrow field for long range detection and tracking. North American Rockwell in their ATS-V study recommended use of a 14° field for acquisition and a 64° field for docking. GE in their study for MSC recommended a 30° acquisition field and a 60° close in field. Bell Aerospace has also recommended use of two fields of view.

An alternate approach to the selectable field of view was proposed by MBA (1971). This concept extends the work begun by CDC in which a foveal 8° field of view is presented to the operator within a peripheral 80° field. The MBA approach is to provide a high resolution stereoscopic foveal 6° field of view and a lower resolution 60° peripheral field of view, all enclosed in a head aimed TV system. In citing the requirements for this degree of complexity, MBA states that, "It is desirable that the visual system should provide most of the capabilities of the human visual system, such as stereoscopy ...(and) eye acuity matching (wide field low resolution combined with narrow field high resolution)." (MBA 1972, Vol. II, pg. 25) As stated in Chapter 7, the requirement for head aimed TV to control camera parameters remains to be demonstrated. The justification for pursuing research on the application of eye acuity matching is easier to make, based on field of view requirements. No such justification was developed by MBA. The basic problems with this approach are: 1) it interferes with the operator's view of other displays; 2) it requires a head aimed type of control to direct the foveal view within the peripheral view; 3) it could cause confusion or disorientation, particularly in the area where the transition is made from narrow to wide field of view. While it is too early to specify this dual field of view as the concept to be implemented in the viewing system of the teleoperator, it is apparant that the approach is promising and deserving of additional evaluation.

2. Motion Resolution

The parameter of motion resolution was deemed important for about 70% of the retrieval tasks and two-thirds of the servicing tasks. Requirements range from 5 arc minutes/sec to 5°/sec for retrieval and from 8 arc minutes/sec to 1°/sec for servicing. It is recommended that a motion resolution capability of 5 arc minutes/second be incorporated into a teleoperator video system.

3. Frame Rate

Frame rate requirements were generally identified for the same tasks which required motion resolution. Of these for satellite servicing, two-thirds required a high frame rate for accuracy of motion resolution, while about half of the servicing tasks requiring motion resolution also required high frame rate. Other researchers are not in agreement as to the required rate with JPL recommending 40 frames/sec, Bell recommending 30 frames/sec, Martin recommending 20 frames/sec and GE recommending 10 frames/sec. Additional research is required to determine the degree of degradation of human visual performance with rates less than 30 frames/sec. Based strictly on operator requirements and not considering the effects on bandwidth and power requirements, a rate of 30 frames/sec is recommended.

4. Brightness

The level of brightness of the monitor should be adjustable with a maximum value of about 100 ft. Lamberts. This will require a source intensity of 50,000 ft. candles for 20 feet viewing and a satellite reflectivity of 80%. The value cited by Bell, 13,000 ft. c., is entirely too low.

5. Depth of View

The requirement for stereo viewing in teleoperator systems has been debated for several years with no real resolution reached as of this date. It is generally conceded that 3D improves performance but what is uncertain is the question of whether the degree of improvement is great enough to warrant the cost. MBA and GE recommend stereo viewing, MBA for the foveal field of view and GE for the entire field prior to docking. GE recommends mono viewing for satellite servicing tasks and mono viewing for all operations is recommended by Bell, Martin and North American Rockwell.

Requirements listed in Tables 57 and 58 indicate that depth of view is required for about one-third of the satellite retrieval tasks and about 60% of satellite servicing tasks. This finding is in conflict with the GE recommendation that stereo be used prior to docking and that mono be used for servicing, since satellite servicing is seen to include more tasks requiring depth perception than satellite retrieval. The minimum values of stereo acuity (the ratio of the interpupillary distance times the offset distance to the square of the viewing distance) is 5 arc minutes for retrieval tasks and 3 arc minutes for servicing, both of which are well above the threshold of 12 arc seconds measured in ideal, laboratory conditions.

The argument concerning the need for stereo viewing in remote handling operations was summed up by Knowles for Wright Patterson in 1962. This author stated that "stereoscopic viewing is often cited as a much longed for and vitally needed feature. But there is room for considerable skepticism as to whether the advantages, if any, would be worth paying for. Most manipulation, though it takes place within the range of effective stereoscopic vision, probably relies most heavily on monocular depth cues. Furthermore, for precise placement in three dimensions, two orthogonal views are probably superior to a single stereoscopic view. Two orthogonal views provide readymade indices, in terms of the framing effect of required control outputs. Stereo-depth probably does not provide as readily interpretable cues."

The present author has had occasion to perform block stacking exercises using a single arm manipulator and one or two view mono TV. Results from these pilot investigations, conducted at the PE and PT Laboratory at MSFC, indicated that, with single video, errors in block positioning along the viewing axis were as great as ± 6 inches. With a second view oriented at 90° to the first, the stacking task was completed successfully on each attempt. When the second view was placed at 45° from the first, each attempt was still successful but was more difficult and time consuming than the orthogonal arrangement. These data are cited only as indications of possible trends and need to be substantiated with well controlled experimentation.

This author has also participated as a subject in docking simulation studies where the view of the target was presented on mono TV. Results of these investigations, for the LM at Grumman and for the free flier teleoperator at Bell Aerospace, indicated little difficulty in controlling range rates to ± .2 fps, nulling LOS rates to ± .2 fps and estimating range ± 2 feet, using mono black and white television.

Given adequate ranging aids and alignment devices, both at the display and at the satellite, mono viewing is probably sufficient for terminal rendezvous and docking to a docking hatch. The question of the need for stereo for satellite capture using a manipulator and for satellite servicing must be resolved through simulation and experimentation.

In addition to effect on visual performance, the decision to use stereo or mono TV has impact on other operator activities and requirements. Most stereo configurations available today require viewing through a sighting device, through a hood or through polaroid glasses. Where the operator is required to monitor other displays and view the teleoperator and target directly, such head constraining devices are unacceptable. Based on this consideration and in the absence of hard data concerning relative visual performance capability with stereo vs mono, the mono approach will be recommended with use of orthogonal views for manipulator capture and satellite servicing.

In their discussion of Human Factors in teleoperator design and operation, Johnsen and Corliss (1971) stated that conventional 2D black and white TV gives a rather limited representation of the complex scenes an operator needs to interpret. Use of color 3D video was evaluated in the early 50's at the AEC Nuclear Reactor Test Site as part of the Aircraft Nuclear Propulsion (ANP) program. The system was discarded for mono black and white. The authors stated that the experiment was premature and represented an unnecessary setback for 3D TV. Due to equipment difficulties with early stereo and color systems, visual performance was degraded and the stigma has remained with such systems to this day. The authors conclude that in the ensuing years advances have been in TV technology which would ensure the success of the ANP experiment if repeated today.

In their simulation of teleoperator pilot operatons in the ATS-V despin mission, North American Rockwell reported that consideration was initially given to using a stereo camera system. Pilot-in-the-loop tests showed no need for this added complexity and pilots were able to judge range and range rate adequately on the basis of stadia without the aid of a stereo image. In these simulations the 3 sigma (.9974 probability) values obtained for lateral miss distance at contact was 2.4 inches and the value for closing velocity at contact was .22 feet per second.

Studies to identify the utility of stereo TV in form recognition tests indicate that stereo has no differential effect than 2D viewing for such a task. Stereo viewing does not significantly enhance the recognition of unfamiliar forms (Paine, 1964; Freeberg, 1962).

6. Direct Viewing

One final consideration for the development of visual display design criteria was the use of direct viewing as a supplement to video. All organizations involved in developing shuttle attached teleoperator concepts cite the requirement for direct viewing (MSC, MBA, Martin and North American Rockwell). Martin recommends a direct field of view of ± 30° lateral, 55° upward and 20° downward.

The need for a direct view of the attached teleoperator and satellite is mainly to provide a panoramic view of the entire situation to the operator to enable him to identify potential contingencies and maintain spatial orientation. Less importantly, it also has the psychological benefit of enabling the operator to see the real world rather than being completely dependent on and constrained by the electronic media. Trading off these considerations vs the impact of including the window into the shuttle is beyond the scope of this study. If it can be shown that a direct view significantly contributes to mission safety by enabling an early identification of off-nominal trends, and if this cannot be achieved by means of video, then the window should be included.

7. Summary of Visual System Tradeoffs

The visual system recommended based on existing data has the following characteristics:

Number of lines - 525

Frame rate - at least 30 frames/second

Size resolution - 5 arc minutes
Field of view - single 44° or two fields using 44° and 10°
Monitor brightness - adjustable up to 100 ft. L.
Monitor size - no more than 7 inch vertical
Depth of view - 2D two orthogonal cameras
Motion resolution - 5 arc min/sec.

CHAPTER 9

AUXILIARY SENSOR AND DISPLAY TRADEOFFS

In addition to requirements for video systems, the development of display design criteria also dealt with computer generated display, force feedback, tactile display and manipulator position/rate display.

1. Computer Generated Display

Requirements for computer generated display in satellite retrieval missions were identified in Table 28 for the free flier and in Table 29 for the attached. For the free flier, computer support was identified for 21 tasks of which 11 require some application of computer generated graphics. These include:

- Generation of teleoperator, shuttle, target, sun geometry display
- Generation of range and range rate envelopes
- Generation of inspection routines and strategies
- Generation of display of satellite cynamic conditions
- Generation of attach point location aids
- Generation of arm position and orientation display
- Generation of trouble-shooting aids and decision trees

It is recommended that specific computer displays and display formats be developed and coded for quick callup. It is also recommended that a TV monitor be provided specifically for computer display of graphic and alpha-numeric data. In addition, consideration should be given to having the computer draw the display aids required for ranging and alignment which will be overlaid the video image of the target.

2. Force Feedback

The need for force feedback and tactile displays over and above visual displays of force/torque and contact must be based on additional research. At present no real requirement for kinesthetic display of force and touch can be identified other than the desire to give the operator a feeling of presence at the worksite. The tasks identified for satellite retrieval and servicing are not of the high precision, high dexterity types which usually require force/touch sensing. Therefore, pending further research, these displays will not be recommended.

3. Manipulator Position Display

The final issue to be considered in this assessment of display design requirements is the display of manipulator position, rates and orientation. When no such display is provided and all the operator sees is the end effector, manual control of the position of the effector becomes difficult since information concerning changes in the arm as a result of control inputs is not available. The minimum requirement then is a view of the entire working manipulator arm. The next question is, is it necessary for the operator to know joint angles, rates, and torques or only general arm orientation? If the operator had a display of angles, rates and torques for each joint he would still need to integrate these data for one joint mentally with data on other joints, which would probably be a difficult and time consuming task. Two other options involve computer generated display of the arms and advisory display only of the fact that certain joints are reaching their maximum capability in terms of angles, rates and torques. The available alternations for display of arm position and orientation are as follows:

- video view alone

- video view and position controller feedback (exoskeleton or mechanical analog)
- video view and dedicated display of joint angles, rates and torques
- video view and advisory display of joints at the limits of angle, rate and torque
- computer generated display

The relative effectiveness of each of these five approaches was established for 10 criterion measures (Table 61). As indicated in this table the computer generated display approach was the most effective followed by the use of video and advisory displays. For the teleoperator system display subsystem both of these approaches are recommended.

TABLE 61 Relative Ranking of Manipulator Position, Rate, Torque Display Options

	Options				
Criteria	Video Alone	Video & Kinesthetic	Video & Dedicated Display	Video & Advisory Display	Computer Generated Display
Simplicity	1	3	4	2	5
Integeration with control	2	1	3	5	4
Interference with other display	3	5	4	1	2
Effectiveness in resolving problems	5	4	2	3	1
Effectiveness for display of gross arm motions	3	2	4	5	1
Minimum workload	2	5	4	3	1
Minimum number of displays	1	4	5	3	2
Effectivenss in maintaining orientation	4	2	5	3	1
Display flexibility	5	4	3	2	1
Operator intergration sum of information	4	3	5	2	1
	30	33	39	29	19
OVERALL RANKING	3	4	5	2	1

CHAPTER 10

CONTROL AND DISPLAY DESIGN REQUIREMENTS

The control/display requirements are summarized below. Design requirements for displays are presented in Table 62 and for controls in Table 63.

Number and Location of Operators - one, in shuttle for attached, in sortie can for free flyer

Control Systems and Operational Concepts Related to Control

- Type of control
  - Free flyer satellite retrieval - basically manual
  - Attached teleoperator satellite retrieval - computer assisted
  - Satellite servicing - manual
- Target attach point tracking - free flyer
  - Undetermined between manual grappler or vehicle
  - Control or automatic grappler control
- Station keeping - undecided between manual or automatic (computer assist) control
- Satellite contact control - automatic grasp based on manual input
- Type of contact - Free flyer and attached - single point contact using a single grappler which may vary in terms of available degrees of freedom
- Despin force application - grappler rigidization or cage motor
- Satellite preparation - Safeing - undecided between automatic, preprogrammed, or manual
- Satellite emplacement into the shuttle bay - Attached - one arm automatic control
- Satellite servicing manipulator - undecided
- Number of arms for satellite servicing - one for actual servicing and one or more for stabilization
- Type of modules used in servicing - standardized
- Type of manipulator controller - satellite retrieval and servicing, free flyer and attached - undecided
- Integration of manipulator and mobility unit control - use of computer assisted control
- Video control - manual

Display Systems and Operational Concepts Related to Display

Ranging - provision of a range and range rate sensor on the free flyer

Rotation rate measurement - use of video aids and/or special sensors. Requirements are undefined.

Force/torque sensing at contact - use of force/rate readout display

Monitor position of attached manipulator - video and direct view

Video resolution - 525 lines

Frame rate - at least 30 frames/sec

Size resolution - 5 arc minutes (.03 inch at 20 inch viewing distance)

Field of view - 44° or 10° and 44°

Monitor brightness - adjustable to 100 ft. L.

Monitor size - 7 inch vertical or less (11 in. diagonal)

Depth of view - 2D - two orthogonal views

Motion resolution - 5 arc min./sec

Support display - computer generated display

No force or tactile feedback

Position display - computer generated and advisory display

TABLE 62 Control Console Displays

Displays	Type	Data Source	Units	Range & Scaling
TV 1 TV 2 TV 3 TV 4	Provisions for up to 4 11-inch monitors	TV cameras or computer		Resolution - 5 arc min. motion resolution - 5 arc min/sec
(2) Contact	Light	Contact sensor	On-off	On throughout contact of effector with target
Camera pan-tilt	Duel meter	Camera position sensor	Degrees	TBD
Camera boom position	3" meter	Boom position sensor	Degrees	TBD
(2) Grip span	3" meter	Grip pickoff	Inches	TBD
(2) Grip force	3" meter	Effector force sensor	Lbs.	0 to 20 steps of .5 lb
(2) Grip torque	3" meter	Effector torque	In-lbs	0 to 10 steps of .5 ft/lbs
Event timer	5 digit readout	Clock	Min - sec	Up to 999 min 59 sec
Time of day	4 digit readout	Clock	Hrs - min	24 hrs 50 min
Max angle	8 lights - each arm	Sensors each joint	On-off	Light illuminates when associated joint is within 10% of its maximum angle
Max force	8 lights - each arm	Sensors each joint	On-off	Light illuminates when maximum force or torque is applied to a joint
Force/rate at despin	Readout	Grappler	Lbs and RPS	TBD
Arm backoff	Lighted pushbutton	Switch activation	On-off	Switch lights when backoff is selected. Light extinguishes on second depression
Arm return	Lighted pushbutton	Switch activation	On-off	Switch lights when a position is indexed - extinguished on return

TABLE 62 - Continued

Displays	Type	Data Source	Units	Range & Scaling
Arm hold	Lighted pushbutton	Switch activation	On-off	Switch lights during hold extinguishes for normal
Range and rate	Tape display integrated with central video monitor	Sensor	Feet and fps	Up to 2000 ft in range in units of 10 ft to 100 ft, .5 ft to 0. Rate - up to ±10fps steps of .1 fps

TABLE 63 Control Console Controls

Controls	Type	Output Destination	Effect
(2) Manipulator controllers	6" joystick or isometric stick, or analog controller	Manipulator joints or computer	Control rate of position of joints/limbs
(2) Free flyer controller	6" joystick	Vehicle attitude and translation	Change position/ orientation
(3) Pan & tilt	1 1/2 inch 4 way switch	Camera pan - tilt	Control camera pan & tilt
(1) Boom control	1 1/2 inch 6 way switch	Camera boom	Control angle and extension of camera boom
Comm panel	Rotary or pushbuttons	Intercom	Select station and call
Keyboard	10 button	Computer	For computer interface
(2) Joint lockout	4 position rotary	Elbow-shoulder wrist or off	Locks out selected joint
(2) Sensor control	Rotary - up to 6 positions or 6 toggle switches	Sensors (undefined)	Select mode of operation of operational sensors
(2) Light angle	Rotary	Light position	Change angle of illumination in one plane
(2) Light intensity	Rotary	Light	Change intensity of illumination
(3) Zoom	Rotary	Camera zoom	Change zoom
(3) Field of view	Toggle	Field of view of camera	Change FOV
(2) Gain	Toggle	Manipulator	Change manipulator gain
Event timer	2 pushbuttons	Event timer	1 pushbutton for timer start - stop 1 for reset
(8) TV controls	Rotaries	TV	Controls for brightness, contrast
(4) TV mode	Rotary	Camera or computer	Select mode for each tube-driven by camera or by computer

TABLE 63 - cont'd

Controls	Type	Output Destination	Effect
(Several) Dedicated function switches	Pushbutton	Computer	Select for display specified computer data format
(4) Camera	3 position rotary	Camera	Select camera to drive each tube
(2) Backoff	Pushbuttons	Arm 1 or 2	Activation drives effector straight back - 8 inches
(2) FOV Mode	Toggle	FOV Control	Selects normal FOV at setting of FOV toggle or shared FOV (foveal - peripheral)
(2) Arm Return	Pushbuttons	Arm Position memory logic	1st depression indexes the position to be returned to 2nd depression returns the arm to that position
(4) Arm mode	2 Pushbuttons each arm	Arm 1 or 2	Select store or zero position
(2) Arm hold	Pushbuttons	Stick	Depression locks out the stick and holds the arm in the last commanded position. Second activation returns stick control

CHAPTER 11 OPERATOR REQUIREMENTS

The interrelationships between operator requirements and man-machine interface design have been taken into consideration as a design concept was developed. One of the criteria considered as alternate allocation approaches were developed to assign system functions to man or machine and for operational tradeoffs was the workload imposed on the man. Another factor taken into account in development of a control concept was number of crewmen involved.

1. Workload

The principle operator requirements include workload, skills and manning levels. The concept of workload includes consideration of the level of activity imposed on the operator and the relative difficulty or complexity of the activity level. The basic constituents of workload are:

Time to perform activities
Number of activities
Number per unit time
Number to be performed simultaneously
Time of simultaneous activity performance
Number of highly complex activities
Number of moderately complex activities
Number of minimally complex activities
Number of tasks which are time constrained

The time to perform all activities is an important determiner of workload since it establishes the time frame required for all activities. In and of itself it is not too meaningful a measure since it does not describe the work going on within the time period. Likewise the number of activities to be performed serves as a general index of workload in that the number identifies the quantity of discrete activities which must be performed within the time period. The measure of number of activities per unit time is a meaningful measure of workload in terms of time limitations alone. It states the average time allocated to the performance of each task. This measure does not account for simultaneous tasks nor of the relative complexity of the tasks. The proportion of the total time spent in completing two or more tasks simultaneous is a valid measure of the worklord in terms of loading of concurrent activities. The final component of workload is the complexity or difficulty of the activities to be performed. Complexity in this context shall refer to the requirement for close attention and close control. The constituents of workload are therefore:

Rate at which activities must be performed
Proportion of total time spent in simultaneous activities
Proportion of total time spent in highly complex activities

An evaluation of the relative workloads for the free flier retrieval, attached retrieval, and satellite servicing missions is presented in Table 64 (based on data from Tables 49, 50 and 51). As indicated in this table free flier satellite retrieval is the mission having the greatest workload while satellite servicing has the lowest workload associated with it. In order to verify the order of magnitude of these estimates, workloads were developed for four of the satellite servicing missions described in detail by GE (1969). The workload measures for these four missions, presented in Table 65 ranged from .65 to 1.07. The measure for the satellite servicing mission in the present study was .52 which indicates that workload estimates developed in the present study are probably conservative.

It is interesting to note the amount of time estimated for highly complex activities in Tables 64 and 65. This time is up to 46% for a retrieval mission and up to 74% for a satellite servicing mission. The activity requiring the greatest proportion of this time for a satellite servicing mission is removal and replacement of bolts, screws, etc.

The approach to measuring workload described above is appropriate for describing the relative workload estimates among various candidate missions. The measure is inappropriate for such decisions as the adequacy of the workload or the need to reduce workload. In order to have a criterion level for selecting or rejecting workload estimates, acceptable levels of each of the three factors (rate, proportion simultaneous and proportion highly complex) must be established. At present no data are available for setting levels of these factors nor for establishing qualified relationships among the factors.

2. Skills

The analysis of skill requirements for satellite retrieval and servicing missions indicates that at least the following skills, in order of relative importance, are necessary:

1. Manipulator operation
2. Docking
3. Image interpretation
4. Computer operation - data handling
5. Fault isolation - troubles hasting
6. Fault detection
7. Flight control - other than docking
8. Communication
9. Cargo handling - other than docking
10. Navigation

TABLE 64 Workload Measures for Satellite Retrieval and Satellite Servicing Missions

	Free Flier Sat. Ret.	Attached Sat. Ret.	Satellite Service
Time to perform (min.)	68	167	157
Number of activities	8	17	28
Number per unit time	1/8.5 min.	1/10 min.	1/5.6 min.
Rate (activities per minute)	.12	.10	.18
Number simultaneous activities	3	2	0
Time of simultaneous activities	20 min.	30 min.	0
Proportion of total time	29%	18%	0
Number highly complex activities	5	6	4
Number moderately complex	2	8	13
Number minimally complex	1	3	11
Proportion of time - highly complex activities	46%	35%	34%
- moderate compexity	44%	46%	37%
- low complexity	10%	19%	29%
Workload			
Rate + proportion simultaneous + proportion high complexity	.87	.63	.52

TABLE 65 Workload Measures for GE Satellite Servicing Mission

	Remove Battery Control System	Battery Replace	Gas Recharge	Replacement of Data Handling Equipment
Time to perform	220	352	70	256
Number of activities	52	114	23	73
Number per unit time	1/4 min.	1/3 min.	1/3 min.	1/3.5 min.
Rate (activities/minutes)	.25	.33	.33	.29
Number highly complex	10	30	5	24
Number moderately complex	22	54	12	29
Number minimally complex	20	30	6	20
Proportion of time - highly complex	40%	40%	74%	50%
- moderately complex	20%	26%	17.5%	30%
- low complex	40%	34%	8.5%	20%
Workload				
Rate + proportion high complexity	.65	.73	1.07	.79

CHAPTER 12

ADDITIONAL RESEARCH AND ADVANCED TECHNOLOGY DEVELOPMENT REQUIRED

In the description of the Teleoperator Systems Human Factors Research and Technology Development Program (Malone, 1971), R and AD requirements were presented based on four missions, two earth orbital and two planetary surface. The areas of R and AD, by priority, were:

1. Display and feedback
2. Obstacle/hazard detection and avoidance
3. Navigation
4. Man-systems integration - including simulation technology
5. Controls and control systems
6. Manipulator - effector design

This listing of important areas can be used to classify R and AD requirements for satellite retrieval and servicing missions with one modification. Since the earlier program was directed toward surface as well as orbital missions, the navigation area took in more importance than would be warranted for a strictly orbital orientation. For this reason the navigation requirements will be considered of minimal importance.

1. Display and Feedback

A program of visual display research and technology development was established which would comprise three general steps. These include: stage 1, static evaluation of video systems; stage 2, dynamic evaluation - video and manipulator systems; and stage 3, hardware simulation, video, manipulator and mobility systems. The objectives and test equipment/facility requirements for these stages are presented in Table 66.

Table 66

Visual System Simulation Objectives, Equipment and Facilities - Each Stage

	Objective	Test Equipment	Test Facilities
Stage 1 Static evaluation of video	1. Evaluation of 3D video vs 2D 2. Evaluation of 3D and 2D video parameters	- A visual task board - 3D video - Variable 2D video - Instrumentation to record performance - Simulated Solar illumination	- A room at least 10 x 12 ft. with electrical interfaces for video and instrumentation lines - Visual barrier between subject and task board
Stage 2 Dynamic evaluation - video and manipulation	1. Evaluation of eye-hand coordination 2. Determination of visual requirements for servicing, maintenance, repair tasks 3. Determination of display requirements and aids for pre-docking operations	- A manipulator task - Initially 1 manipulator - Eventually 2 manipulators (ADAMS) - Manipulator control system - Instrumentation - Simulated Solar illumination - Simulated Artificial illumination - 3D video - Variable 2D video - A target model and drive system - A video camera drive system - Equations of motion - Computer interface - Control console	Same as Stage 1 or 3 basic facilities: - Target drive - Computer complex - Control station
Stage 3 Hardware Simulation video, manipulation and mobility	Determination of visual system requirements in conjunction with manipulator-mobility unit requirements	- Air bearing platform and floor - Target models - Mobility unit with manipulators - Video system - Computer interface - Control console	Air bearing facility Computer facility Control station

Stage 1 Description - Static Evaluation

The dual objectives of this stage are to evaluate the effectiveness of stereo TV systems and to evaluate the effects of varying levels of 2D and 3D video parameters. For this simulation, a visual task board will be constructed which will include tests of operator capability to:

- identify forms and patterns
- judge distances and relative displacements
- detect small targets
- detect small rates of motion
- estimate size of targets
- estimate rates of motion
- detect changes in displacement
- discriminate different levels of brightness
- estimate slope
- estimate the vertical
- estimate alignment of pins

The operator will perform required activities with the visual task board under varying configurations of the video system. The video parameters to be varied will include:

Sensor

field of view - from 15° to 60°

resolution - 500 to 1000 lines

zoom - 1X to 10X

number of cameras (2D) - one or two

- camera location
    - boresighted
    - offset (10° to 45°)
    - 1 boresighted and 1 offset (30° to 90°)
    - offset camera aspect - overhead or side
- Display
  - noise levels - best and worst case
  - distortion levels - best and worst case
  - monitor size - 8 inch to 18 inch
  - number of monitors - 1 or 2
  - contract capability - varying shades of grey
  - number of lines - 500 to 1000
  - frame rate - 1 frame/sec to 30 frames/sec
- Target Illumination
  - brightness
  - number of lights
  - area coverage
  - direction of incident light
  - condition of light - diffuse or collimated

The results of this simulation will establish operator capabilities with alternate configurations of 2D and 3D video sensor and display parameters and target lighting conditions. The results can also be used to establish the relative performance of operators with 2D vs. 3D systems.

The essential equipment item for this simulation is the visual task board which will consist of a set of visual tests to include testing of:

- Perception of depth - alighment of two adjacent vertically oriented pins which will vary in size and lateral displacement. Judgments will be made as to whether the movable pin is in front of, aligned with or in back of the stationary pin. Results will indicate operator capability of judging displacement in the frontal plane.

- Perception of distance - operators will estimate the displacement of two pins in the frontal and lateral planes. Results will establish the capability of the operator to judge distance.

- Detect small targets - operators will be presented with targets of varying size and brightness contrast to determine their capability of detecting these targets.

- Perception of form and pattern - operators will be presented various forms and patterns and will be asked to match these with standard forms and patterns presented in different orientations.

- Perception of motion - operators will be presented with different size targets moving at different velocities and in different directions. They will be asked to (a) determine if the target is moving, (b) at what rate, and (c) with what displacement over time.

- Brightness discrimination - operators will be asked to match the perceived brightness of two adjacent targets.

- Perception of the vertical - operators will be required to judge if a displayed target is parallel to or perpendicular with the vertical and, if not, what is the angular offset.

- Alignment - operators will estimate the alignment and offset of two pins in the frontal plane.

The results of these tests will serve as the basis for developing a description of the performance capability of the video systems which will be used in later simulations, and for establishing the relative performance capability of the human observer under varying conditions of video parameters.

Stage 2 Dynamic Evluation of Video/Manipulator Interaction - Satellite Servicing

This test will employ selected visual system parameters based on the analysis of stage 1 data and the 2D and 3D video systems used in the earlier stage. A manipulator task board will be designed and fabricated to measure the effectiveness of the visual system in performing and directing specific satellite servicing tasks. Specific requirements for a test of video requirements in satellite inspection and spin rate determination are presented in Table 67.

Stage 3 Hardware Simulation

This stage will entail a simulation of the visual system as a portion of the entire manipulator system.

Table 67

Satellite Inspection and Spin Rate Determination

Objectives:

- Assessment of operator capabilities and limitations
- Display design development and integration
- Design of alignment-sighting aids and devices

1. Simulation Requirements

- Computer based simulation of free-flying vehicle rendezvous, station keeping, inspection of stabilized and spinning satellites
- TV view from the vehicle
- System to drive a satellite scale model in 6 degrees of rotational and translational
- Solar light simulation (collimated) source at 150 ft.L. effective brightness at the CRT
- Star field background for initial acquisition and rendezvous
- Mathematical model to enable the selection of errors due to gyro drift, misalignment, sensor accuracy limits, etc.

2. Test Planning

- Performance measures

  rendezvous miss distances
  range estimation
  velocity vector control accuracy
  propellant management
  time to complete and accuracy of selected operations
  (spin rate determination)
  inspection accuracy
  attitude control accuracy

- Independent variables
  video - 2D and stereo
  display parameters
  satellite spin - wobble rates
  sighting aids, spin rate determination aids, alignment aids

Table 67 (continued)

- Control variables

    satellites
    initial conditions
    magnitude of errors
    operator procedures

- Test conditions

    set of conditions based on selection of combinations of levels of independent variables

- Data analysis

    multivariate analysis of variance with option of covariances (Essex has Computer Program)
    description of mean and variance for each measure
    trend analysis
    correlation of performance on each measure for each condition and across conditions
    comparison of data with standards (fuel budgets, time constraints, standoff distance tolerances) and prediction of performance with a 95% level of confidence

<u>3. Mockup Requirements</u>

- Target

    model and drive, model lighting, background

- Remote manipulator

    camera drive

- Control console and experiment monitoring console

    video
    controllers - attitude and translation
    indicators - attitude and rates, V

- Acceptance criteria for consoles and model drives

Table 67 (continued)

4. Computer Programs

- Equations of motion - model and camera
- Interface with controllers
- Error models
- Interface between data tape and analysis program
- Printout requirements

5. Data Acquisition - Recording

- Strip chart recorders for on-line monitoring
- X-Y plots
- Data recorded on mag tape
- Time referenced record of controller position

6. Simulation Checkout

- Verification of dynamics - responses
- Identification of problems

7. Subject Selection & Training

- Classroom instruction - orientation
- Practice of maneuvers
- Actual training to a specified proficiency level

8. Experiment Monitoring

- 2 man console - human factors specialist and test engineer
- Repeat video view presented to subject
- Repeat indicators at console
- Display propellant quantity in %
- Display actual (simulated) range, range rate and line of sight rates

Table 67 (continued)

9. Conduct of Tests

- Assume three months running time

10. Analysis of Data

- Data reduced prior to printout
- Analysis via tape interface

11. Interpretation of Data

- Data interpreted during test conduct to enable modifications in test plan as required
- Human Factors assessment of performance effectiveness in completing acquisition, rendezvous, station keeping, inspection, maneuvering around the satellite, and determination of spin characteristics

Other display areas requiring additional research include development of concepts for aids and sensors for measurement of satellite rotation, video field of view requirements and interactions with other subsystem parameters, and display integration techniques.

2. Obstacle/Hazard Avoidance

Research is needed to develop requirements for and design concepts of contact sensors. While research should procede on tactile sensors and touch displays, these items are not considered essential for the early satellite retrieval and servicing missions.

3. Man-Systems Integration

The only essential item of development in this area is a reliable and valid simulation technology for teleoperator systems simulation. To date the primary zero g simulation technique deemed appropriate for teleoperator systems has been the air bearing approach. The basic difficulty with this approach is the loss of the vertical dimension of motion. Consideration must be given to the impact of this loss and to methods of enhancing the fidelity of teleoperator simulation.

The following presents the activities to be accomplished in developing a high fidelity, reliable and valid teleoperator simulation program:

1) Simulation Fidelity Analysis

For each parameter identified under performance requirements and constraints for each mission to be simulated, the level of simulation fidelity will be established. This assessment will be based on an evaluation of the simulation objectives and will determine the degree to which the fidelity of the system and subsystems influences the simulation data reliability and validity. The evaluation will require that each parameter associated with the system and subsystem be analyzed to its elemental "dimensions of fidelity". For the parameter "dexterity" under the subsystem "manipulators and effectors", the dimensions of fidelity would include:

C.3

- degree of articulation
- force application capability
- grip capability
- force gradients
- available effector motions
- smallest object capable of being held, handled, manipulated and transferred

Similarly, dimensions of fidelity would be developed for each paramenter of the total system. When the set of fidelity dimensions is complete, a judgment will be made concerning the fidelity level required in the specific simulation for each dimension. The levels will include the following:

Maximum fidelity - maximum fidelity is essential
High fidelity - fidelity close to maximum is required
Moderate fidelity - fidelity can be intermediate between high and low
Low fidelity - minimum fidelity is all that is required

At the same time that these estimates are being made, an evaluation will also be made of what the effects would be of a lower level of fidelity. Thus, for each dimension, the effects of assuming a level one step below the stated required level would be determined for:

Data reliability - degree to which data are repeatable

Data validity - degree to which the data are generalizable to the actual situation

When fidelity levels have been developed for all dimensions of fidelity, the degree of required fidelity for each parameter will be established by rating the parameter according to the following scale:

5 - all dimensions require maximum fidelity
4 - all dimensions require at least high fidelity
3 - dimensions are distributed among maximum or high and moderate or low
2 - no dimension is higher than moderate fidelity
1 - all dimensions are of low fidelity

2) Identification of Available Simulation Resources

The simulation techniques for providing a required level of fidelity for each parameter for each identified simulation will be identified. The available resources within MSFC to provide these techniques will then be established. This assessment will serve to define the existing capabilities to provide the needed simulation fidelity and will serve as one tradeoff criterion. Simulation resources include:

- facilities
- personnel
- equipment off the shelf
- support equipment
- computation equipment
- mockup fabrication

3) Identify State-of-the-Art in Simulation Technology

The state-of-the-art in simulation technology will be reviewed to determine if required equipment and techniques not available at MSFC are available elsewhere. This assessment will also serve as a fidelity-cost tradeoff criterion.

4) Identify Simulation Costs

The monetary cost of planning, fabricating and conducting a simulation study using the stated required levels of fidelity will be identified. This cost figure will consider resources available, new simulation technology required, and costs of mockup fabrication, computer time, support elements, etc. The costs will be developed for a total simulation using required levels of fidelity and for each parameter. Dollar costs will also be developed for reduced fidelity levels associated with each parameter. The cost analysis will require a justification of fidelity levels 5 and 4 for all parameters where a significant cost savings is demonstrated by assuming a lower level of fidelity. No justification will be required of levels 3, 2 and 1 regardless of the cost differential between required and reduced levels of fidelity.

In all analyses, cost data will be segregated by engineering and research costs, development costs, procurement costs, and support costs.

5) Development of Fidelity-Cost Tradeoff Criteria

Criteria for assessing the benefits of a required level of fidelity vs. the cost of providing the level will be developed. These include the following:

- Simulation accuracy
- Simulation reliability
- Simulation data validity
- Use of simulation as a trainer
- MSFC available resources
- Use of state-of-the-art
- Time to initiate simulations
- Time to complete simulations
- Engineering cost
- Development cost
- Procurement cost
- Support cost

6) Conduct of Tradeoffs

Tradeoffs will be conducted between simulation approaches using stated required fidelity and approaches using reduced fidelity. Weighting factors will be established for each tradeoff criterion in consultation with MSFC cognizant personnel. The association of weighting and ratings for each parameter of each identified simulation will determine if the required fidelity is feasible within cost limits or if reduced fidelity is feasible, when resulting in a cost saving.

7) Development of a Recommended Simulation Approach

Based on the fidelity-cost tradeoffs and the assessment of available simulation resources at MSFC, an approach for the identified simulation study will be developed. This approach would include such techniques as 1 g computer driven, 6 df zero g device, neutral bouyancy, air bearing, or KC-135 parabolic flight. In the case of the lunar rover, all simulations of the control station would be conducted in a 1 g environment since the mission control center would be on earth. In the orbital free flying T/O case, however, the 1 g environment or any one of the zero g simulation techniques would be selected based on fidelity requirements.

The simulation approach would also consider other factors in addition to the gravity environment as dictated by the fidelity-cost tradeoff. The degree of precision to be incorporated into the simulation will be determined by the results of this tradeoff. Thus, the accuracy of math models, manipulator responses, handling qualities, etc., will be defined by the outcome of the trade studies.

8) Identification of Simulation Requirements

Based on the selected approach for simulation, the simulation requirements will be established. These include such factors as:

- Mockup requirements
- Logic requirements
- Response and error model requirements
- Support requirements
- Fidelity requirements
    - each parameter for each subsystem and mission
- Data acquisition and recording requirements
- Data analysis requirements
- Monitoring requirements

9) Develop Integrated Simulation Plans and Schedules

For each identified simulation, a plan and schedule will be developed which takes into account the simulation requirements and available simulation resources. This plan will include schedules for mockup development, math model development, test conduct and data analysis.

10) Development of Requirements for Advanced Simulation Technology

For simulations requiring technology beyond the state-of-the-art, requirements will be developed for advanced technology. This will include development of advanced equipment and use of innovative techniques. Requirements for advanced simulation technology will apply to simulation studies further along the development process, but plans for the development must be developed as early as possible.

11) Development of Techniques to Validate Simulation Data

This step essentially defines the techniques required to correlate data received from actual flights with those data obtained in simulation tests. This validation is essential to ascertain the validity of currently available techniques of simulation as evidenced by the Gemini XII verification of in-flight data with neutral bouyancy data.

As an ancillary task in this study, an evaluation was made of teleoperator simulation facilities and equipment existing at NASA MSFC. The results of this evaluation are presented in the Appendix.

4. Controls and Control Systems

The two basic problems to be attacked in the conduct of R and AD for control systems include: the degree of computer involvement in the control of the teleoperator systems; and the parameters of the manual controllers. Simulation exercises to develop requirements for control systems should parallel those described in the display and feedback section under stage 2 for manipulator control and stage 3 for mobility unit control.

Manipulator degrees of freedom to be controlled:

Shoulder azimuth

Shoulder elevation

Elbow flexion

Forearm rotation

Forearm extension

Wrist rotation

Wrist azimuth

Wrist elevation

Grip open/close - tool operate

Guidelines for controller design:

Requirements to frequently remove the hand or to change hand position and orientation on the stick should be minimized.

Arm response rate should be proportional to stick displacement.

Returning the stick to the detent should result in the arm holding the last commanded position.

Control stops should be incorporated in the manipulator control logic which prevent it from applying a force or torque greater than a specified quantity.

Stick displacement should reflect manipulator response (i.e., a stick pitch up should result in an upward elevation of the arm).

Simultaneous control of 2 or more arm degrees of freedom should be provided.

The stick must be capable of rapid, high-accuracy adjustments.

Operation of the stick should not cause operator hand-arm fatigue.

Operator Functions with the Stick

Functions	Stick Characteristics
Identify controller	Coding-location
Grab controller	Shape-size-orientation
Maintain hand position	Shape-contour-texture
Control manipulator:	
Position	Direction of motion - response sensitivity
Rate	Angle of displacement - response linearity
Acceleration	Rate of displacement
Hold manipulator in position	Detent-spring forces
Contact structures	Contact feedback
Sense applied force/torque	Force/torque feedback

Classification of Stick Characteristics

Physical characteristics

- Type
- Size
- Location/orientation
- Number of sticks
- Shape/contour
- Coding
- Switch design and location
- Texture

Operational characteristics

Degrees of freedom

Direction of motion

Displacement extent

Rate of motion

Spring forces

Detents and dead bands

Controller-display relationships

Response characteristics

Stick-arm relationships

Position-rate feedback

Force-contact feedback

Sensitivity

Linearity

Control Lags

Interfaces

Hand wired to manipulator

Interfaced with logic - for orientation

Interfaced with computer - for shared control

Alternate Approaches and Relative Advantages/Disadvantages

Factor/Alternate Approach	Advantages	Disadvantages
Stick Type		
Gemini Pistol Grip	- Ease of grasping - Large displacement	- Difficult to make rapid, precise and small adjustments
Lm Contoured Grip	- Non fatiguing for long duration control	- Same problem as Gemini grip although not as demanding due to smaller size

Factor/Alternate Approach	Advantages	Disadvantages
Jet Aircraft Controller	- Simple design	- More fatiguing - Extensive use of function switches
T handle	- Good for rapid response operations	- Uncomfortable arm/hand position - Functions change with orientation - Usually less displacement
Pressure Stick	- Good when volume constraints are severe	- No displacement all for rate - Difficult to incorporate force/contact feedback - Requires high workload - Difficult to make rapid and precise adjustments
Finger Tip Stick (ATM Pointing)	- Excellent for small, rapid response, precise adjustments	- Small displacement - Difficult to judge input rate from displacement
Dual stick (pivoted at the base and at the mid point of the stick)	- Increased degrees of freedom - Good stick-manipulator relationships - Enables control of more than 1 manipulator degree of freedom at a time	- Requires hand displacements up and down the stick - Could result in inadvertent actuation
Stick Size		
Large	- Greater control for gross motions	- Degraded control for precise motions
Small	- Greater control for precise motions	- Degraded control for gross motions
Stick location - orientation		
Side arm - vertical orientation (LM attitude control)	- Natural for pilots	- Requires arm rests-supports
Side arm - fore/aft orientation (LM Translation)	- Possibly more natural for upper arm control	- Not as comfortable for long duration control

Shape/Contour	Advantages	Disadvantages
Cylindrical stick	- Simplicity	- Fatigue
Pistol grip - uncontoured	- Retains hand position	- Fatigue
Pistol grip - contoured	- Minimizes hand fatigue while holding hand position	- Variations in hand size could cause difficulties
Pistol grip - contour tailored for specific operator	- Maximum comfort	- Maximum complexity
T handle	- Simplicity	- Fatigue
Finger tip	- Ease of operation	- Requires arm and hand rest
Coding		
Labelling	- Reduces errors	- Increased time to perform
Response directed	- Reduce time due to naturalness of control	- May lead to confusion in some arm orientations
Switch design - location		
Clean stick - no switches	- Reduced workload	- May not have all required degrees of freedom
4 way thumb switch	- Minimal hand motion	- Requires a different operation
Top of stick	- Ease of making 2 control inputs simultaneously	- Hand movement a problem if required frequently
4 way switch-side of stick	- Increased degrees of freedom	- Difficult to actuate - Requires hand motion
Pushbutton - side of stick	- Increased degrees of freedom - Simplicity of operation	- Actuation difficulty - Absence of feedback - No rate control

Trigger switch - front of stick	- Easy actuation - integrated with grip	- Chances of inadvertent actuation
Stick Texture		
No texture	- Hand motions easier	- No hand retention
Texture	- Facilitates hand retention	- Reduces freedom of hand motions
Stick degrees of freedom		
Maximum through stick minimum by switches (dual pivoted stick)	- No hand motions required to operate switches - Stick-manipulator relationships more natural - Time to perform operations minimized - Minimal problems of switch inadvertent actuation	- Control of a minimum number of df simultaneously - Problems in getting 8 or 9 arm df from the basic 4 stick df
Maximum through switches minimum through stick	- Simple design - Enables simultaneous control of more functions - Provides all required degrees of freedom	- Requires frequent hand displacements on the stick - Increased change of inadvertent actuation - Increased change of selecting the wrong switch - Increased workload/fatigue
Stick direction of motion		
Two mode stick-switched to model-controls shoulder and elbow, in mode 2-controls forearm and wrist	- Enables all degrees of freedom	- Increased chance of errors - Cannot control upper and lower arm simultaneously - Requires additional switching and a function switch

Stick motion controls shoulder, elbow and forearm switches control wrist and effector	- Enables all degrees of freedom	- Switch problems as cited above
Dual Pivoted Stick lower stick-shoulder, elbow and forearm upper stick-wrist and effector	- Minimal switches	- Hand motion problems - Workload problems
Stick displacement		
Small	- Good for high accuracy and rapid correction	- Minimal rate cue from displacement
Large	- Good cue of rate response	- Difficult for precise control
Rate of motion		
Slow	- Greater range of arm accelerations	- Problems when rapid arm response is required
Fast	- Good for rapid arm response	- Difficult for precise rate control
Fixed	- Minimum workload	- Response may be too fast or too slow in certain situations
Variable	- Selectable for conditions	- Requires an additional switching and a function switch
Spring forces		
Small	- Less effort	- Slow return to detent
Large	- Rapid return	- Greater effort - Difficulty in sensing force

Detents/Deadbands		
Center detent only	- Simple response	- Stick must be held in position for long duration motions
Center detent and fixed detents	- Reduces workload	- Selection of detent positions a problem
Center detent and stick hold detent	- Holds stick whenever positioned	- Increased time to return to center detent
Controller- Display Relationships		
Stick displacement - motion inferred from tip position orientation	- Simple design	- Possibility of errors - disorientation
Stick displacement required always the same regardless of arm orientation	- Reduces errors - Straight forward response	- Required logic
Control linearity		
Linear response	- Direct inference of rate	- Reduced range
Non linear (log) response	- Greater range	- Problems in establishing rate of response

5. Manipulators and Effectors

The evaluation parameters which should be taken into account when assessing the performance of a manipulator design concept include the items listed in Table 68.

A detailed evaluation of a specific manipulator system (the GE ADAMS system) was developed to identify the essential requirements for testing. The results of this analysis are presented in Table 69.

Table 68

Manipulator/Effector Evaluation Parameters

Physical Description

Manipulator

- Type - electric, hydraulic, pneumatic, etc.
- Degrees of freedom
- Number of links
- Number of joints
- Total length
- Length - each link
- Diameter - each link
- Diameter - each joint
- Total weight/mass
- Structural material
- Structural strength
- Structural hardness
- Stowed volume
- Mechanical-electrical interfaces
- Power requirements - average and peak
- Temperature/thermal limits
- Number of arms assumed

End Effector

- Flexibility - Dedicated or Adaptable
- Degrees of freedom
- Type - fixed or modular
- Grip size - span
- Number of attach/contact points
- Manipulator/effector interface

Table 68 - cont'd

Performance Capability

Manipulator

- Functional reach
- Reach envelope
- Weight lifting capability
- Stall torque - each joint
- Deflection force - each link - maximum and minimum
- Angle of rotation - each joint
- Angular rate - each joint
- Angular acceleration - each joint
- Rate gains available
- Stability - loaded and unloaded
  - full reach and full flexion - each joint
- Miss distance
- Minimum positional change - total arm and each limb
- Reach extension
- Drift - loaded and unloaded - 15 minutes at full reach and full joint flexion
- Force/torque sensors
- Limb/joint position - orientation sensors
- Force gradients
- Actuator time lag (to control input)
- Input-output ratio
- Time to perform standard operations
- Integration with video systems

Effector

- Number and types of motions
- Maximum/minimum rate - each motion
- Hand dexterity - smallest object handled
- Hand articulation - number of alternate configurations
- Force/contact/position sensors
- Force/torque range

Table 68 - cont'd

Control System

- Control repeatability - position and rate
- Position - rate indexing
- Positional accuracy
- Control linearity
- Control sensitivity
- Control cross coupling
- Control proportionality
- Control mode - rate or position
- Controller parameters

    - forces - breakout, sustained, hardover
    - angular - linear displacement
    - directionality
    - relationships with arm/hand response
    - detents
    - indexing

- Degrees of freedom controlled
- Position - rate feedback
- Force - torque feedback
- Integration with video systems

Table 68 - cont'd

Maintainability/Safety

- Availability of check points
- Component accessibility
- Component vulnerability
- Modular design
- Failure detection sensors
- Troubleshooting aids
- Replacability of entire unit
- Requirements for spares, special tools, test sets
- Provisions for ground maintenance safety
  - electrical hazards
  - mechanical hazards
  - structural hazards

Table 69

Description of ADAMS Manipulator Evaluation Tests

Test	Measure	Instrumentation
Functional Reach	Each arm reach with effector oriented 0° and 90° WRT work surface	Measure shoulder and wrist angles Measure reach
Reach envelope	Right-left & up-down span for minimum range 1/4 maximum range 1/2 maximum range 3/4 maximum range maximum range	10 curved surfaces 5 for up-down 5 for left-right curvature equal to the arc described by the arm length for each range condition
Weight lifting	At full reach lift weights from floor to shoulder height. Weights vary from 5 to 10 lbs. in 2 oz. increments. Repeat for 1/2 full range and minimum range	Measure force at each joint for each weight - sensors at each joint
Stall torque and force gradients	Rigidly constrain the limbs adjacent to each joint - apply torque and measure stall torque - repeat 10 times for each of the 6 degrees of freedom	Measure torque - each joint - each degree of freedom. Measure gradients of force application
Deflection force	Apply force to each limb for each degree of freedom - record force required to move limb ± 2 inches Repeat 10 times for each direction for each degree of freedom	Measure force at input to limb (external source) Measure deflection of limb
Angles, rates & accelerations	Exercise each arm to determine maximum and minimum angular excursion, maximum and minimum rates, accelerations and decelerations, and time to accelerate/decelerate. Complete in unloaded condition and repeat with load of 6 lbs. at the effector	Angular measures for each limb - accelerometers and timers

Table 69 - cont'd.

Test	Measure	Instrumentation
Stability	Stationary Fit effector with a pencil control pencil point to a target .1 in. in diameter and hold for 30 seconds Complete for full reach forward 30° up and down, left and right of forward axes - at full reach and full elbow flexion - unloaded and with 6 lb. load Repeat 10 times - each condition Dynamic Track lines on paper under conditions listed for stationary with minimum rate	Paper containing target properly positioned for each condition. Measure excursions from the target
Miss Distance	Fit effector with telescoping pointer set for minimum length. Move arm at commanded rate and direction and stop when aligned to a .1" target. No corrections are allowed after the single deceleration to a full stop. Extend the pointer to measure the error in alignment	Need a moving point to establish the commanded rate and direction. The path of the point will bisect the target. Rates will include the minimum and maximum rates established for each arm as well as two intermediate rates to be determined.
Minimum positional change	Fit effector with pencil, align to a target point. Move to other targets located from .1 to 2 in. away. Complete for full and for minimum reach	Set of paper sheets with targets - to be inserted into work board located at full reach and at minimum reach
Drift	Fit effector with pencil - set at a point located at full reach and minimum reach - forward and 30° right and left, above and below the forward axes. Leave for 15 minutes and measure drift. Complete unloaded and loaded with 6 lbs.	
Time lag	Measure time from command input to joint initiation of response	Pickoffs at master joint and slave joint. Signals to strip chart recorder with .1 second accuracy. (moving at a rate of 2.5 in./sec or greater

Table 69 - cont'd.

Test	Measure	Instrumentation
Standard operations		
Removal/ Replacement	Test board with module insert. Located along forward axis and 30° above, below, right and left of forward axis at full reach, 3/4, 1/2 and 1/4 full reach. Modules of 3 sizes, one size requiring two hand removal and two requiring one hand removal. Measure time and forces/torques required to remove a module, place it in a stowage area, acquire a replacement module and replace.	3 axis force sensors along module track. 2 axis torque sensors. Force/torque/rate sensors at each joint for each degree of freedom Sensors to detect angles and motions of each joint
Bolt torque	Test board with bolts of varying size and location. Effector with torque removal tool. Start at standard position of the arm - move the effector to the bolt to be removed, remove it, return to standard position, return to the bolt location and replace, measure time, alignment, forces and torques	Forces and torques - each joint - each degree of freedom. Sensors to detect angles and motions of each joint
Two hand connect/ disconnect	Test board with connectors of different sizes - locations and requiring different activations	Force/torque sensors - each degree of freedom and at the base of each connector. Sensors to detect angles and rate - each joint
Force/torque Application	Test board with variable spring force lever capable of being moved along 3 axes and of being rotated about its longitudinal axis - sized for one and two hand use	Force/torque sensors at the board
Dexterity	Test board with pegs of varying size and location to be removed and replaced	Force sensors to measure forces inward, right & left and up and down. Sensors to detect angles & rates - each joint

Table 69 - cont'd.

Test	Measure	Instrumentation
Standard operations - cont'd		
Antenna deploy	Test board with a telescoping rod fixed at the base. With each arm grasp the end point of the rod and move upward, downward, right, left, inward and outward to extend the rod to maximum extension or to a designated extension.	Force/torque sensors at the base of the rod to measure forces and torques - in 6 degrees of freedom. Timer to measure time to perform. Scaling on rod to measure accuracy.

6. Operator Requirements

Research is required to quantify and measure operator workloads. These measurements must be sensitive to changes in load and to the performance implications of the workloads. Analysis and research are also required to identify teleoperator operator skills and skill levels required to successfully complete satellite retrieval and satellite servicing missions.

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