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EARTH ORBITAL TELEOPERATOR SYSTEM MAN-MACHINE INTERFACE EVALUATION

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FOREWARD

The Teleoperator System Man-Machine Interface Evaluation Program outlined in this report reflects the joint effort of NASA MSFC teleoperator systems personnel and Essex Corporation in developing and implementing a program to determine human performance requirements in teleoperator systems.

The NASA engineering staff involved in this program include Mr. Wilbur G. Thornton, Mr. Carl Huggins, Mr. Al Kosis, Mr. Stark Cline, Mr. Herman Blaise, Mr. Tom Barnes, Mr. Frank Vinz and Mr. Linnis Thomas. The Essex research program was performed under NASA contract NAS8-28298. This report constitutes a partial fulfillment of the requirements specified in that contract.

Initial reporting of experimental findings covered in this program is to be found in Kirkpatrick, Malone, and Shields, Earth Orbital Teleoperator Visual System Evaluation Program, Essex Corporation, 303 Cameron Street, Alexandria, Virginia.

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1.0 INTRODUCTION

In seeking to establish effective roles of man and machines in space flight of the future, NASA has evolved the concept of remotely manned systems. These systems, designated as teleoperators, are differentiated from manned or automated systems in that, on the one hand, the man is not present at the worksite, and on the other the man is still an integral element in the control loop. A teleoperator system is characterized by the fact that some spatial extent separates the man from the worksite, and also in that he controls the operations of the system at the worksite from a remote location. The teleoperator, therefore, constitutes a viable alternate to the use of manned and automated systems since it has, at the same time, the significant advantage of the manned system (man's adaptive intelligence and problem solving ability) with the durability, strength, and expendable nature of the machine.

In order to investigate the applicability of teleoperator systems for NASA advanced space missions, and to coordinate and focus the teleoperator research and technology development within NASA, a NASA Committee on Teleoperator Technology has been established. This committee has allocated roles and responsibilities to various NASA field centers for development of teleoperator systems technology. The allocations were such that the Johnson Space Center was designated responsible for the shuttle attached manipulator system, JPL for the Lunar/Planetary rover system, Ames for advanced teleoperator technology, and Marshall Space Flight Center for overall earth orbital teleoperator technology, and for the free flying teleoperator (FFTO) flight experiment.

Man is an integral component of a teleoperator system. This follows from the fact that he is active in the system control loop, and due to the fact that the essential reason for being for the system is to enhance and augment his capabilities and to extend these capabilities beyond his physical presence. Since man occupies a prominent position in the teleoperator system, a good deal of attention needs to be given to the man-machine interface in the development of teleoperator technology. This interface comprises the aspects of the system hardware and software which affect man's performance, his safety, and his overall effectiveness in his designated position. The interface also includes the human element, the man with his unique and specific capabilities and limitations, and requirements and constraints.

In December 1971, the Essex Corporation contracted with NASA Marshall Space Flight Center to provide the analyses, research, and design inputs relative to the development of technology for the man-machine interface for earth orbital teleoperator systems. The teleoperator man-machine technology development activity has been integrated with the overall earth orbital teleoperator technology development effort at MSFC, as described in the MSFC Teleoperator Technology Development Plan. This plan identified technology development activities leading up to the technology ready date for the free flying teleoperator system of 1977. This report describes in summary form the methods employed and results of the first two years of teleoperator man-machine interface research and technology development. Section 2.0 presents a summary of the evaluation effort in each of the primary technology areas, while Section 3.0 describes the results of the free flying teleoperator mission analysis. Three accompanying volumes describe in detail the technology development activities for the visual system, manipulator system, and vehicle control system.

1.1 Teleoperator Man-Machine Interface Technology Development - Overview

The significant inputs to the teleoperator man-machine interface technology development program are teleoperator mission applications and associated mission requirements and constraints. The primary outputs are man-machine interface design criteria and concepts. The program itself is concerned with developing design criteria and concepts from mission requirements and constraints. As described in the MSFC Teleoperator Technology Development Plan, this is accomplished through the integrated application of three distinct activities: man-systems analysis, engineering design and concept development, and developmental and concept verification testing.

A. Analytical activities include the identification, analysis, and integration of mission and system requirements. For the earth orbital teleoperator technology development program missions where teleoperators offer advantages are generally typified as support missions: shuttle payload support; payload experiment support; and shuttle support. In addition, a free flying teleoperator flight experiment mission is being considered. The types of mission classes for each of these types of support missions are as follows:

Payload Support Missions

- Payload retrieval (capture and recovery to the shuttle from low earth orbit or geosynchronous orbit)
- Retrieval support (preparation of payloads for retrieval or final emplacement in the bay)
- Payload deployment (removal of payloads from the bay and placement in low earth orbit or geosynchronous orbit)
- Deployment support (preparation for placement in orbit, including shroud removal, spin up, and orbital readiness test)
- Payload servicing (maintenance, re-supply, refurbishment)

- Payload assembly (module mating, erection)
- Payload inspection (surveillance and fault detection)

Experiment Support Missions

- Data acquisition (sensor placement and control)
- Experiment servicing (re-supply, refurbishment)
- Experiment deployment (assembly, erection, placement)

Shuttle Support Missions

- Inspection (e.g., heat shield damage assessment)
- Servicing of shuttle systems
- Engineering data acquisition (plasma wake sampling)
- EVA astronaut support (rescue, assistance)

A teleoperator man-systems analysis of the payload retrieval and servicing mission classes was performed by Essex in a contract to MSFC prior to the initiation of the current effort (NASW-2220, Malone, 1972). This analysis resulted in baseline functional flow block diagrams depicting functions and relationships among functions to be performed by a teleoperator system in the conduct of generalized satellite retrieval and servicing missions. The analysis further identified system performance, information, and decision requirements associated with each function, and established the criteria for allocation of system functions to human or machine performance.

The teleoperator man-machine interface evaluation program used the requirements generated in this earlier effort (NASW-2220) as well as the outputs of an assessment of teleoperator performance requirements developed by the URS/Matrix Company in 1972 (NAS8-27013), and a free flying teleoperator experiment definition program conducted by Bell Aerospace (1972-73, NAS8-27895 and NAS8-29153). These sources provided the teleoperator mission and system requirements which supported the development of the evaluation program in general, and the selection of evaluation tests in particular.

The teleoperator systems addressed in this program included the free flying teleoperator system, the space tug teleoperator system, and the teleoperator tended system wherein the teleoperator system elements are integrated with the payload subsystems. Particular emphasis in the program was placed on the free flying teleoperator (FFTO), since the results of the evaluation program are intended to support the development of an FFTO flight experiment, as well as the development of technology directly applicable to FFTO systems and missions.

B. Engineering Design and Concept Development

The ultimate purpose for the teleoperator man-system analysis activities is to support the development of system and subsystem concepts, and to provide data on human performance capabilities and requirements as inputs to the engineering design of teleoperator systems and subsystems. As requirements for additional data are identified in the analysis, and as concept development proceeds through the series of design decisions and tradeoffs, requirements are generated for empirical data. These data are obtained from experimental tests performed in various laboratories of the MSFC teleoperator technology development program. The objectives of the tests, then, include collection of information to support or supplement the analytical activities, and acquisition of performance data to support the evaluation of concepts under development, and to enable the validation of concepts already developed. The engineering design and concept development activity therefore occupies the central position in the teleoperator technology development cycle. The activity is supported on the one hand by the results of analyses of mission requirements and constraints, system requirements, human capabilities and limitations, and the state-of-the-art in teleoperator subsystems technology, and on the other hand by the results of evaluation tests.

The teleoperator subsystems of primary interest in the MSFC teleoperator technology development program include:

- The manipulator system, including manipulator configuration, actuators, control systems, sensors, and end effectors
- The visual system, including sensors (cameras), displays, display aids, telecommunications, system control, and the human operator.
- The mobility system, comprising the integration of the manipulator and visual systems with the vehicle itself and with supporting subsystems (propulsion, power, structures, and interfaces)

C. Evaluation Tests

During the intial two year period of the teleoperator man-machine interface technology development program, evaluation efforts were conceptualized and, in some cases, implemented in four areas. These included:

- Teleoperator visual system
- Teleoperator manipulator system
- Teleoperator mobility system

1.2 Objectives of Teleoperator Man-Machine Interface Evaluation Programs

A. Visual System Evaluation Program

The teleoperator visual system evaluation program was directed at the following objectives:

1) To determine the relative effects of video system and target parameters on human visual performance capability
2) To develop a data base of human visual performance under varying video system and target characteristics
3) To develop a series of simple standardized tests to evaluate visual performance aspects of candidate visual system concepts.

4) To provide human visual performance capability data as input to visual system design tradeoffs, and to the development of visual system design tradeoffs, and to the development of visual system design criteria

The program established to satisfy these objectives was structured in terms of two different types of tests: static and dynamic. The static test program is directed at establishing human operator visual performance capability along specified dimensions under varying and controlled conditions of video and target parameters. The dimensions of interest include the basic correlates of human visual performance (perception of depth, visual acuity, brightness discrimination, etc.). The results of static tests describe the limits of operator performance capability on each of the dimensions, and define the relative effects of changes in video parameter (frame rate, line resolution, etc.) and target parameters (size, contrast, etc.) on performance.

Dynamic investigations of visual systems are more concerned with the capability of the operator to process and use visual information in performing activities derived from specific teleoperator mission requirements. These tests, conducted for purposes of concept development and verification, and integrated with tests of manipulator and mobility systems, assess total system (man and machine) performance under simulated mission conditions. In these tests measures are acquired of the effectiveness of design concepts in satisfying specific system requirements. The measures include indicators of human performance in the acquisition and integration of visually displayed information and in the use of this information for decision making and performance of a control sequence.

The distinguishing difference between static and dynamic tests is that while static tests may be described as well-controlled laboratory experiments producing data which are generalizable to a wide range of activities and conditions, dynamic tests comprise simulations of well defined teleoperator missions or mission sequences, where obtained data are specific to the particular visual system configuration, system task, and worksite under investigation.

B. Manipulator System Evaluation Program

Technology development for manipulator systems will proceed in parallel with the development efforts for visual and mobility systems. Manipulator system evaluations will be conducted toward the following objectives:

- Evaluate the range of capabilities and limitations of existing manipulator and controller concepts in terms of system requirements associated with specific teleoperator missions
- Support the development of advanced manipulator system and subsystem concepts by producing data used in analytical tradeoffs and in engineering design efforts
- Verify and validate the performance effectiveness of concepts selected on the basis of development tests, analysis, and engineering design
- Establish design criteria for the man-machine interface associated with manipulator system control, visual system integration, and control station design

The manipulator system evaluation program directed toward these objectives, as described in this report, is being supported by a parallel effort comprising a configuration and design study of manipulator systems applicable to the free flying teleoperator, being conducted by Martin Marietta for MSFC.

C. Mobility System Evaluation Program

As defined in the MSFC Teleoperator Technology Development Program Plan, the basic technique for teleoperator mobility system technology development entails an integrated program of engineering analysis and design, and conduct of controlled hardware simulation studies for concept development and design evaluation. The analysis and design activities will proceed at the two levels of system technology and subsystem technology development. Subsystem technology will entail integration of available and advanced subsystem technologies into an effective system concept.

Simulation tests conducted to support mobility system development will comprise two types or levels: part task simulation and full task simulation. Part task studies will include research and design development studies conducted for subsystem technology development. Full task simulations will be reserved for development and verification of system technology.

Objectives of tests performed in the mobility system evaluation program are as follows:

- Provide data to support development of concepts and design criteria for teleoperator subsystems (guidance and control, sensors, control station, and support systems)
- Provide data for teleoperator system concept development and verification
- Support analytical and design efforts involving integration of visual and manipulator systems with the mobility system

2.0 TELEOPERATOR SYSTEM MAN-MACHINE INTERFACE

The Teleoperator System Evaluation Program described in this report reflects the joint effort of NASA MSFC teleoperator systems personnel and Essex Corporation in developing and implementing an experimental program to determine human factors design requirements for earth orbital teleoperator servicing and retrieval missions. The experimental effort summarized here represents a continuing implementation of the teleoperator technology development plan in three primary areas:

- Visual system evaluation and development
- Manipulator system evaluation and development
- Vehicle mobility system evaluation and development

The visual system evolution is described in two separate sections, reflecting the classification of visual system tests as static and dynamic. The static tests involved laboratory tests of basic human visual performance as a function of video and target characteristics. The dynamic test program involves visual simulations of teleoperator mission operations, such as rendezvous and docking.

This section summarizes the present status and test planning for these three technology areas.

2.1 Visual System Tests - Visual System Test and Evaluation Laboratory

This subsection is concerned with the continuing effort to identify the visual system requirements for remotely manned systems. The visual system evaluation program is designed to determine the effects of visual system design parameters on the operator's ability to perform visual tasks associated with teleoperator mission functions. The details of the laboratory apparatus, procedures, and findings have been presented in two previous reports, Kirkpatrick, Malone, and Shields (1973) and the results of four tests completed since the publication of these reports are summarized in the present report. The above reports may be consulted for detailed information on these tests. The studies conducted are briefly summarized below:

(1) Distance Estimation - This investigation dealt with the operator's ability to judge depth and relative distance between two objects when the center of the field of view for one orthogonal camera is aligned behind the target objects. The subject was required to estimate the absolute separation distance bewteen two target pegs and report his level of confidence in that decision. He was further required to determine which of the two target pegs appeared closest to him. Four camera modes were utilized involving one monoptic view, a three dimensional view and two conditions of two camera monoptic views. The placement of the target pegs was controlled about the center line of the forward half of the task table.

(2) Motion Detection - This test involved the operator's ability to perceive fore/aft translation of the target object under varying rates and fields of view and under conditions of display aids and no display aids. Two conditions of reticles were used and a condition of no reticle aid was employed. A target motion generator produced translation of the target along the camera's line of sight. The subject was to determine any motion of the target after a two second view of the TV picture. Five rates and two directions (toward and away) along with a zero rate were studied.

(3) Motion Detection - The operator's ability to perceive fore/aft translation of a target object under varied TV system parameters using reticle display aids was studied, as in (2) above.

(4) Target Non-Alignment - Dealt with the operator's ability to perceive non-alignment of a solid cylindrical target object normal to the camera line of sight under varied lighting conditions. The subject reported when he could detect non-alignment and the direction of non-alignment of a simulated satellite under lighting conditions which approximated a teleoperator attached artificial light source and a natural (sunlight) lighting condition.

Laboratory Apparatus and Procedure

All experimental testing was done in the teleoperator visual systems test and evaluation laboratory at the Marshall Space Flight Center. All equipment in the laboratory was of the commerical "off the shelf" variety. Two cameras were available for imaging the test scene; both were 525 line systems having a standard video bandwidth of 4.5 MHz. Both of the cameras were capable of being band limited at either 1 MHz or 500 kHz. The output from either camera could be routed through a digital data system, which converted the analog composite video signal to digital code. This data system was adjusted to give an image of 2, 4, 8, or 16 shades of gray through the system. The signal was then reconverted to analog to provide the image displayed on the observer's monitor. Two levels of noise were added to the video presentation giving a choice of signal-to-noise ratios of 21db and 15db. A ratio of 32db was used as the baseline level. Additional equipment used included a standard Stereotronics stereocaptor with operator's polarized glasses and associated polarized monitor face plate. These items also were off-the-shelf, commercial items. The

Target Motion Generator (TMG) used in motion detection experiments, and the general laboratory/task area are described in detail in

The general testing procedure was as follows: the subject was instructed as to the task he was required to perform during each test situation. The experimenter set up a test scene before the camera and then switched it on the subject's monitor, or monitors. This switching started a clock to time the subject's response. The subject decided on the interpretation of the view and pressed the corresponding switch at his position, removing the view from the screen, and stopping the clock at the experimenter's station.

Six subjects (four male and two female) aged 24 to 30 years of age, were selected for the studies following screening for normal vision. Selection criteria for subjects was based on the absence of visual anomalies on standard orthorater visual examinations.

The system and target parameters investigated in the various experiments are listed in Table 1. In Table 2 these parameters are noted by visual test.

Test Results

(1) Distance Estimation - The significant sources of variance were found to be camera mode, fore/aft displacement, lateral displacement, and the camera mode by fore/aft displacement interaction. Four camera modes were used:

1. 2 camera 2D configuration, 0° & 90° left
2. 1 camera 3D split image, 0°
3. 1 camera 2D configuration, 0°
4. 2 camera 2D configuration, 0° & 45° left

The camera mode 1 yielded the lowest mean absolute error magnitude of separation estimation (.75 in.) while camera mode 4 yielded a mean absolute error magnitude of (1.96 in.) followed by camera mode 2 (1.86 in.). These results tend to support previous data gathered under similar conditions (Kirkpatrick, et al, 1973).

Fore/aft and lateral separation also showed a significant influence on mean absolute error magnitude in that mean error increased as separation distance increased. A complete discussion can be found in Kirkpatrick, Shields, and Malone, 1973.

While stereoptic viewing per se had little effect on reducing mean absolute error magnitude, it did yield the lowest probability of error associated with the task of determining which of the two targets was closer to the operator. This probability of error was simply the frequency over all trials where the operator judged incorrectly that a particular target was closer to him. Using this measure, camera mode 2 yielded a probability of error equal to .20.

(2) Motion Detection, Fixed Visual System Parameters - Under conditions employing a visual system with 30 frames/sec, 32 db S/N ratio, 4.5 MHz analog signal, and a 20° field of view the following results were noted:

- That for a 3 foot (diam) target at a 20 foot range an absolute value of range rate in feet/second of .16 ft/sec is necessary for fore/aft motion detection (along the camera's axis) at the .95 probability level. With a detection probability of .50, that absolute value of range rate decreases to .05 feet/second.

(3) Motion Detection, Variable Visual System Parameters - Under conditions employing a visual system with the following variable parameters:

- Frame rate - 15 or 30
- Signal-to-noise ratio - 15, 21, or 32 db
- Transmission mode - analog - 4.5 MHz
  analog - 1.0 MHz
  digital- 4 bit

and with a 20° angular field of view, the following results were noted:

- Neither frame rate, signal-to-noise ratio nor transmission mode was found to have a significant main effect on motion detection. The only effect of frame rate was noted under reduced horizontal resolution in the analog mode. It was worthy to note that in contrast with prior studies (Kirkpatrick, et al, 1973), signal-to-noise variation failed to exert a significant effect on motion detection for the values studied.

(4) Determination of Target Non-Alignment - The significant effect found in this experiment was the intensity of the auxiliary light source, with the higher levels showing a decrease in the number of degrees of offset necessary for the operator to detect non-alignment of a target.

In previously reported findings on detection of non-alignment it was reported that for the target employed, non-alignment away from the predominant light source is detected at smaller angles than is non-alignment toward that light source. The current data continue to support that initial finding.

Discussion of Results

The results of all studies of the teleoperator visual system performed in the Visual System Test and Evaluation Laboratory are summarized in this section. The results of the first eleven experiments (Kirkpatrick, et al, 1973) yielded the following conclusions.

Small Target Detection requires that the displayed image size be from 4 to 20 arc minutes subtended at the operator's eye. The 4 to 20 arc minute range is for 90% probability of detection and the exact value depends on signal-to-noise ratio and other transmission parameters.

Within the constraints of the experiment, detection performance was not strongly influenced by bandwidth reduction from 4.5 to 1 MHz nor by introduction of digital signal processing as long as signal-to-noise ratio remained above 20 db. Reducing signal-to-noise ratio to 15 db, however, produced a marked decrement in performance when transmission mode was varied.

Brightness Discrimination - Probability of brightness discrimination error was found to depend on contrast and transmission mode. With direct (4.5 MHz) transmission, contrasts greater than .2 were detected with near certainty. Under 4 bit digital transmission, error rates remained in the 5 to 10% range for contrast ratios as high as .50.

Size Discrimination - In judging which of two targets appears larger, response time shows little improvement with signal-to-noise ratio increases beyond 21 db. Digital transmission degrades response time relative to direct transmission. Similar effects were noted for response accuracy as measured by the probability of incorrect response. In addition, target-background contrast strongly influences probability of error. Under low contrast (.125), linear size differences of ±30% could be detected with near-zero error rates. Under high contrast (.625), however, this discriminable size difference threshold value was reduced to ±10%.

Target Size Estimation - Performance in estimating the size of a single target viewed via TV was found to be sensitive to signal-to-noise ratio increasing markedly with a change from 21 to 5 db. Increasing the ratio to 32 db, however, had little effect. Mean absolute size estimation error was found to depend primarily on true target size and target-background contrast. Mean absolute error expressed as a percentage of true size varies from 10 to 40%.

Shape and Pattern Recognition - When subjects were required to recognize familiar geometric shapes, it was found that visual angle required for recognition varied from 25 to 40 arc minutes depending on target shape. Strongly angular shapes (traingles, rectangles) require smaller subtenses for recognition than do circles and hexagons. In addition, performance in recognizing angular shapes is relatively insensitive to signal-to-noise ratio and transmission mode.

Judgements of Separation Along the Fore-Aft Axis - Eight camera/display systems were evaluated in terms of absolute error in estimating the fore-aft displacement of two target objects. These included single channel monoptic viewing, two channel monoptic viewing, two camera stereoptic viewing, and single camera split field stereo viewing. Over the range of displacements studies, the minimum error system employed two monoptic cameras placed orthogonally in the target X-Y plane. A single camera stereo system placed in front of, and higher than the task board and tilted down at 45°, was found to yield the next lowest absolute error. Little evidence was found to support the notion that stereoptic systems per se provide better depth judgement. The error rates for the various systems studied depend on camera location relative to the targets. Over most of the displacement range studied, single camera monoptic viewing with the camera higher than task board and tilted down at 45° was not found to be much less effective than stereo viewing from the same position. Indeed, the monoptic 45° was not found to be much less effective than stereo viewing from the same position. Indeed, the monoptic 45° tilt condition was found to be superior to several stereoptic systems investigated and its performance was not improved by addition of a second monoptic view in the target plane.

Judgements of Alignment of a Solid Target - Subjects were required to judge whether the longitudinal axis of a cylindrical target object was aligned with the camera viewing axis or was displaced in pitch or yaw. Error rates were found to be strongly influenced by the angle between the target axis and the light source used in the experimental apparatus. When the target axis was within 30° of the light source, non-alignment angles of 10° were not detected in 65% of the trials. This finding appears to warrant studies of artificial lighting systems for the teleoperator to be used in judging alignment prior to docking.

Estimation of Horizontal and Vertical - Subjects were required to judge whether a straight line presented via TV departed from the horizontal or vertical. Performance in this task was found to be largely independent of signal-to-noise ratio and transmission mode effects. The threshold angular value for near-certain detection appears to be about ±3°.

Based on the data reported here, the following general conclusions are warranted:

(1) Mean visual angle required for detection of small objects or gaps between larger objects varies from 3 to 9 arc minutes depending on signal-to-noise ratio and transmission mode. Equations are presented for use in deriving field of view requirements from target size and detection range requirements.

(2) Over a wide variety of visual tasks, performance is degraded by a reduction of signal-to-noise ratio from 21 to 15 db. In no case, however, did an increase in the ratio from 21 to 32 db result in performance gains. A signal-to-noise ratio in

the vicinity of 21 db appears to be adequate for performance of the tasks studied here.

(3) Over a number of the tasks studied, narrow band and digital transmission modes result in performance degradation relative to direct analog TV viewing. In arriving at a decision on the transmission system for a baseline teleoperator, task performance will have to be traded off against power and bandwidth.

(4) Contrast between target and background is a crucial parameter in size judgements. Since these judgements will provide much of the basis for range estimation by the operator, contrast ratios on the order of .60 should be provided between the teleoperator arm or end effector and the satellite.

(5) In the case of reduced target-background contrast, size estimation errors will increase and performance in estimating range will be impaired. It may, therefore, be necessary to incorporate some form of adjustable scale cursors, crosshairs or stadia or other TV aids into the video system. The alternate would be to develop a range sensor and display.

(6) Where the operator is required to judge if a uniform cylindrical target is aligned with the camera viewing axis, performance is strongly dependent on the direction of non-alignment with respect to the direction of the predominant light source. For worst case lighting, 10° non-alignments were detected in only about 35% of cases. This figure contrasts strongly with other lighting conditions studied where 5 to 7° non-alignments were detected with near certainty. In docking with a satellite, the performance requirements placed

on the operator in terms of alignment tolerance will depend on the grappler design but if the mean detectable non-alignment angle exceeds 10° in some cases, methods for improving this performance appear worthwhile.

(7) In a wide range of relative distance estimation, performance was found to depend strongly on the camera mode and camera/workspace geometric relationship. Within the constraints of the experiment, no general superiority of stereoptic viewing was identified. Where two video channels were employed, provision of orthogonal views generally led to more accurate distance estimation than did combining the two channels into a single stereo view. It was found that operator performance was more sensitive to camera placement than to camera mode (i.e., stereoptic or monoptic). Based on these experiments, the provision of a boom mounted camera system which can be optimally placed for manipulation functions appears to outweigh provision of stereoptic viewing as a teleoperator design requirement.

The above findings are the result of a series of experiments performed in a previous effort and reported in detail elsewhere. The intent of the four studies reported here was to further investigate some of the previous results and to begin an experimental analysis of range and range rate estimation when satellite/teleoperator relative motion is involved.

Stereo TV Evaluation

The stereoptic TV evaluation reported here was initiated to explore the effect of orthogonal viewing on distance estimation reported previously in Experiments 7, 8, and 9 (Kirkpatrick et. al., 1973). The distance estimation task with orthogonal viewing had the property that the target objects were both moved fore and aft in the main field of view so that they were equally displaced from the center of the field of view of the secondary camera. In the real world application, this would require precise camera positioning during manipulation. It appears more likely that the operator would initially position the camera systems to provide a general view of the worksite and would not adjust this view with any great frequency. The consequence is that the distance being judged would not always be centered in either field of view. Accordingly, a variation of the task was employed which varied the locations of the target objects in the orthogonal camera field of view.

The results of this experiment were found to be in good agreement with the previous results. In terms of absolute estimation error, the two-camera orthogonal viewing mode was found to produce significantly improved performance relative to the other camera modes studied. The finding that camera positioning more strongly influences performance than does stereoptic vs. monoptic viewing was also supported. Stereoptic viewing did produce fewer errors in deciding which target was closer and yielded smaller estimation errors for zero target displacement. That is, when no target separation existed, operators were better able to diagnose this fact using the steroptic system than using any other system. As true separation increased, however, up to the limit of 8 inches studied here, the estimation error obtained with the orthogonal system remained relatively constant whereas error magnitude increased linearly with true separation for the remaining systems.

The results show that the improved performance noted with orthogonal viewing is not reduced by moderate departures from orthogonality. It is not necessary that precise adjustment of the orthogonal camera be maintained. The finding supports the previous conclusion that the teleoperator visual system should include provision for near-orthogonal positioning of two cameras during on-site servicing operations.

The remaining three experiments reported here relate to maneuvering and final approach to the satellite rather than to manipulation functions.

Solid Target Alignment

The study of solid target alignment reported here was a follow on the the experiment reported by Kirkpatrick et. al. (1973). In the previous experiment, departure from alignment of the target and camera viewing axis of 10° were detected only 35% of the time under conditions where the non-alignment direction coincided with the direction of the predominant light source.

Three questions were raised by the previous experiment. The maximum non-alignment angle available with the apparatus employed was 10° so that mean non-alignment detection performance for worst case lighting geometry could not be quantified. One objective, then, was to study this performance variable. Second, the previous findings suggested that non-alignment detection should depend heavily on the angle sun-teleoperator-satellite. The third objective was to determine to what effect, the operator's ability to detect non-alignment under worst case sun geometry could be improved by artificial lighting and to establish required lighting parameters.

The findings relative to these questions are shown in Figure 12 which has already been discussed in detail. For worst case sun geometry and no artificial lighting, mean non-alignment required for detection reaches nearly 40°. It is difficult to see how a docking mechanism could be designed which would tolerate altitude errors of this magnitude. Performance can be dramatically improved if the teleoperator approach path minimizes the sun angle. Since the approach path will be constrained by other factors, however, the best approach to the problem lies with artificial lighting. The data obtained showed that introduction of an artificial source oriented along the camera viewing axis can both render performance independent of sun angle and reduce the mean detection non-alignment angle to levels approximating the original best case condition - that obtained when the non-alignment direction is away from the predominant light source.

The question of parametric lighting levels was addressed by the current study. Artificial luminance in the range of 20 to 70 foot lamberts was investigated. The data showed a reduction in mean non-alignment angle for detection of approximately one degree for each additional ten foot lamberts. Whether these lighting levels are realistic for a teleoperator system is a question for further system definition studies. A trade-off is evident here between available power and operator performance. The finding that artificial lighting may be a design requirement based on system performance during final approach has not been identified previously. There is little doubt that the free-flying teleoperator will be equipped with a lighting system.

Tewell et. al. (1973) have conducted parametric studies of lighting requirements during servicing. A requirement for lighting during final approach, however, could be a design driver since the source to target distance would presumably be greater during approach than during servicing.

Range Rate Detection Experiments

Correct control of range during final approach and docking operations requires that the operator receive adequate feedback concerning range and range rate. One approach would be to provide dedicated displays of these variables based on output from an appropriate sensor such as radar. This approach has associated problems - particularly range measurement at very short ranges during the final portion of the approach. In view of these considerations, a portion of the MSFC teleoperator effort is devoted to studying alternative methods of range and range rate estimation - including optical. If the visual system could assume the range feedback function, the engineering complexity and cost of a dedicated ranging system could be avoided. To date two aspects of the problem have been investigated. Laboratory studies of operators' ability to detect a non-zero range rate have been performed and an analytical study of a dynamic reticle system for range rate estimation has been carried out and will serve as a basis for future experimental investigations. The two experiments carried out on range rate detection performance relate to the requirement for the operator to null range rate at various points in the mission. The corresponding empirical question is the ability of the human operator to judge whether range rate is positive, zero, or minus from a brief exposure to the video scene.

The results of two experiments suggest that optical ranging may be a feasible mode insofar as simple rate detection is concerned. Smoothed data with a stationary reticle and undegraded image quality showed the range rate for .95 detection probability to yield approximately .027 in 1 sec^2 in image size on the monitor. For a Bio-Research Module having a diameter of 3 feet, a 20^{o} field of view, and a range of 20 feet, the corresponding range rate is about .17 ft/sec. This represents about a one percent error suggesting considerable sensitivity of the operator to range rates.

A second experiment requiring range rate detection under conditions of degraded image quality found no significant decrement in performance due to main effects of reduction of frame rate from 30 to 15 frames per second, reduction in signal-to-noise ratio from 32 to 15 db, reduction in bandwidth from 4.5 to 1 MHz or introduction of 4-bit digital signal processing. A joint effect of frame rate and transmission mode was identified in that a significant performance decrement was obtained due to frame rate reduction with a 1 MHz bandwidth.

Compared with transmission parameter effects noted in Kirkpatrick et. al. (1973) for static visual judgements, the effects found for range rate detection are minimal. The sensitivity of the operator to range rate is not influenced by fairly wide variation in image quality. This suggests that if ranging were allocated to the visual system no delta in visual system requirements based on other visual tasks would be imposed. It should be noted that this conclusion is supported by the data to date but deals only with range rate detection. The question of the visual system with suitable reticles to serve as the sensor for range rate estimation must still be resolved. This will be the objective of studies to be carried out in the near future.

2.2 Visual System Tests - Computer Based Docking Simulation Technique

The initial phases of a teleoperator servicing or retrieval mission involve translation to the vicinity of the satellite, station keeping, final approach, and docking. During this approach, the system operator must control attitude and translation and make a variety of judgments concerning relative motion via both television and numerical displays. The computer controlled docking simulator at NASA MSFC Computations Laboratory was employed to study operator/system performance during translation and final approach.

The simulation technique employed a six degree of freedom motion generator to impart apparent motion to a scaled satellite model. The operator viewed the target satellite via closed circuit television and attempted to complete the final approach using translation and attitude controllers. The control commands from the operator's station were sensed by a hybrid computer system which solved a sixteen thruster propulsion system math model using assumed vehicle mass, thrust, and dynamic parameters. The resulting position and attitude values were then used to control the target motion generator.

The simulation system components included:

- Target Motion System (TMS) which employed servo controlled gimbal systems to produce relative motion between the satellite model and the television camera.
- Operator's station including an 18 inch television monitor, range and attitude displays, a translation controller and an attitude controller.
- Analog-Hybrid Computer System which accepted the operator's

control commands and solved a relative motion math model. The model employed is described in the Teleoperator Docking Simulation Report. The assumed propulsion system was the baseline system proposed by Bell Aerospace (Fornoff, et al, 1972).

Experimental Procedure

A single trial in the sumulator was divided into four mission phases as follows:

- Translation from an initial simulated range of 70 meters to a station keeping range of 6 meters.
- Station keeping at fixed range. During this time the operator estimated the dynamic parameters of the satellite motion.
- Track attach points by matching teleoperator motion to the attach point motion resulting from satellite nutation.
- Final approach during which the subject attempted to close the range while maintaining attach point tracking. After the subject committed to docking, the run was terminated when range was reduced to .6 meter.

Subjects received detailed instructions on the operation of the system. They were allowed to practice the task until they considered themselves familiar with it. Four subjects were used throughout the study. Subject selection criteria included pilot experience, degree in technical area, and "normal" vision for pilots. The subjects ranged from 28 to 42 years of age.

Independent Variables and Experimental Design

The independent variables manipulated in the current study included:

• Satellite nutation angle	0, 2, 4, 5, 10 degrees
• Satellite nutation rate	0, 2, 4, 5, 10 RPM

- Initial starting position and orientation
- Attitude control system deadband 1° and 2°

The following parameters were held constant:

- Satellite type - Large Space Telescope
- TV aids - Concentric ring reticle
- Initial range - 70 meters

Each subject underwent all possible combinations of nutation angle, nutation rate, and attitude control system deadband. These treatment combinations of nutation angle, nutation rate, and attitude control system deadband. These treatment combinations were presented in a randomized order. Initial position and attitude were randomized for each trial subject to the constraint that the target always appeared in the television field of view at the start of the trial.

Dependent Measures

The dependent measures recorded were elapsed time and propellant consumption. Both measures were scored independently during each phase and were summed to yield total mission measures.

Results

Mean elapsed time and mean percent of propellant consumed were analyzed as functions of nutation and rate. Both variables were found to be more strongly influenced by nutation angle than by nutation rate. A least-squares curve fitting analysis showed that most of the effect of nutation angle on total mission time and fuel consumption is exerted during phase 4 - final approach.

Subjects reported difficulty in holding alignment with the satellite attach point as nutation angles and rates increased. When either nutation angle reached above 5° and exceeded 5 RPM, subjects were unable to maintain attach point tracking. When this occurred they abandoned the attempt to maintain continuous alignment and simply attempted to match the attach point motion at one point in time committing to docking if their timing of the maneuver appeared acceptable.

Planned Studies

Studies currently planned for the simulator involve assessing operator capability to perform final satellite approach using only aided television. No range or range rate displays will be available. Additionally, the set of dependent measures will be increased to include lateral translation and attitude squared integrated error scores. Instantaneous translation and attitude position and rate values will be measured at the completion of each phase. This will permit quantification of range rate control accuracy using only optical ranging and will yield final approach accuracy data in terms of projected aimpoint error and forces at the time of docking contact.

2.3 Manipulator System Evaluation Program

The summary of laboratory conditions and procedures, as well as the objectives of the proposed manipulator experiments are given in this section.

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

The objectives for ten tests utilizing various candidate controllers and manipulators are briefly given as follows:

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

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

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

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

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

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

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

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

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

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

Table 1 contains a general event schedule for any one of the manipulator tests. Table 2 indicates the relationship between mission requirements and each of the selected tests. Table 3 presents the system and performance parameters associated with each test.

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

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

Figure 2 lists the general experimental flow as it applies to the testing procedures.

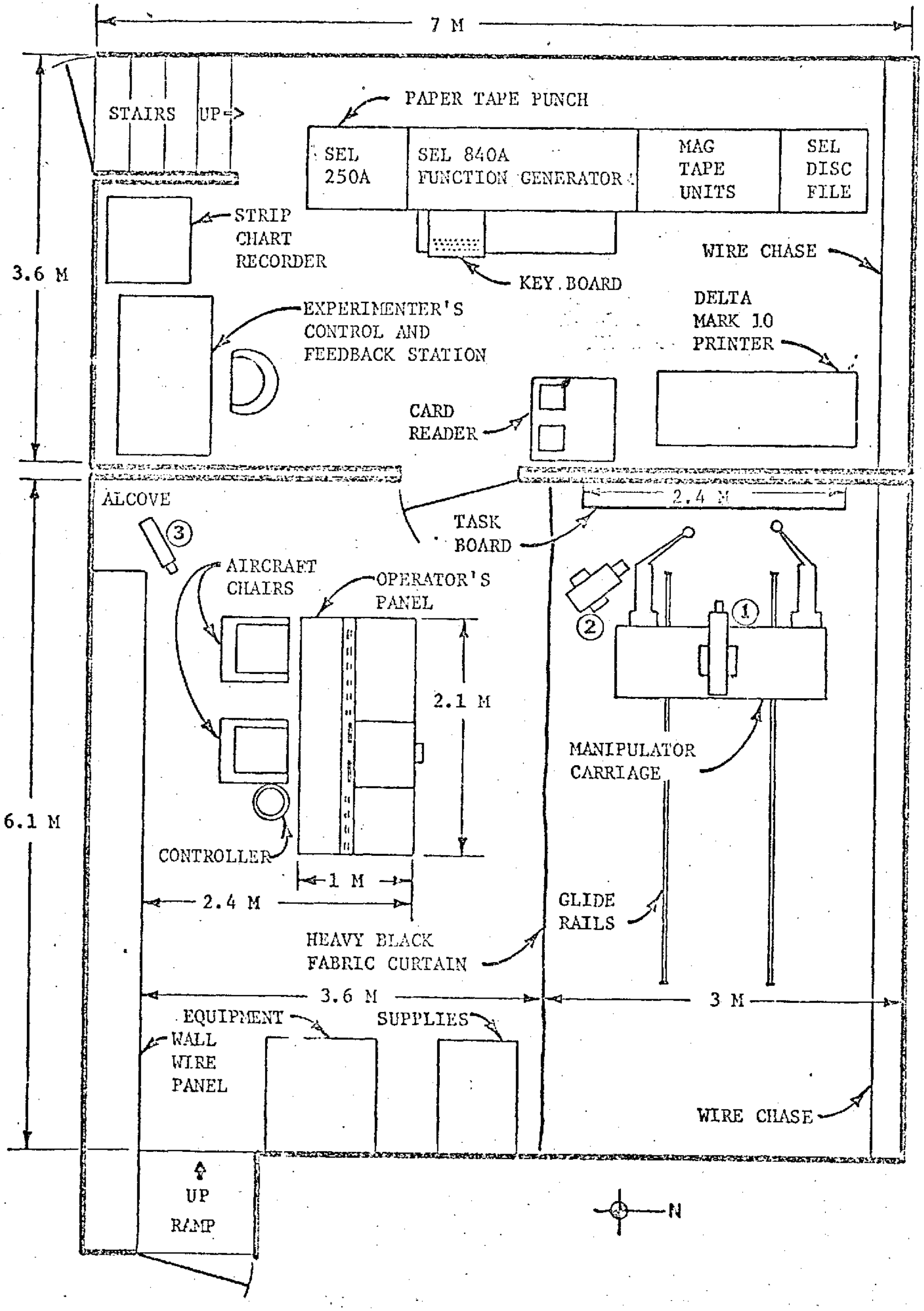

FIGURE 1. Manipulator System Evaluation Laboratory

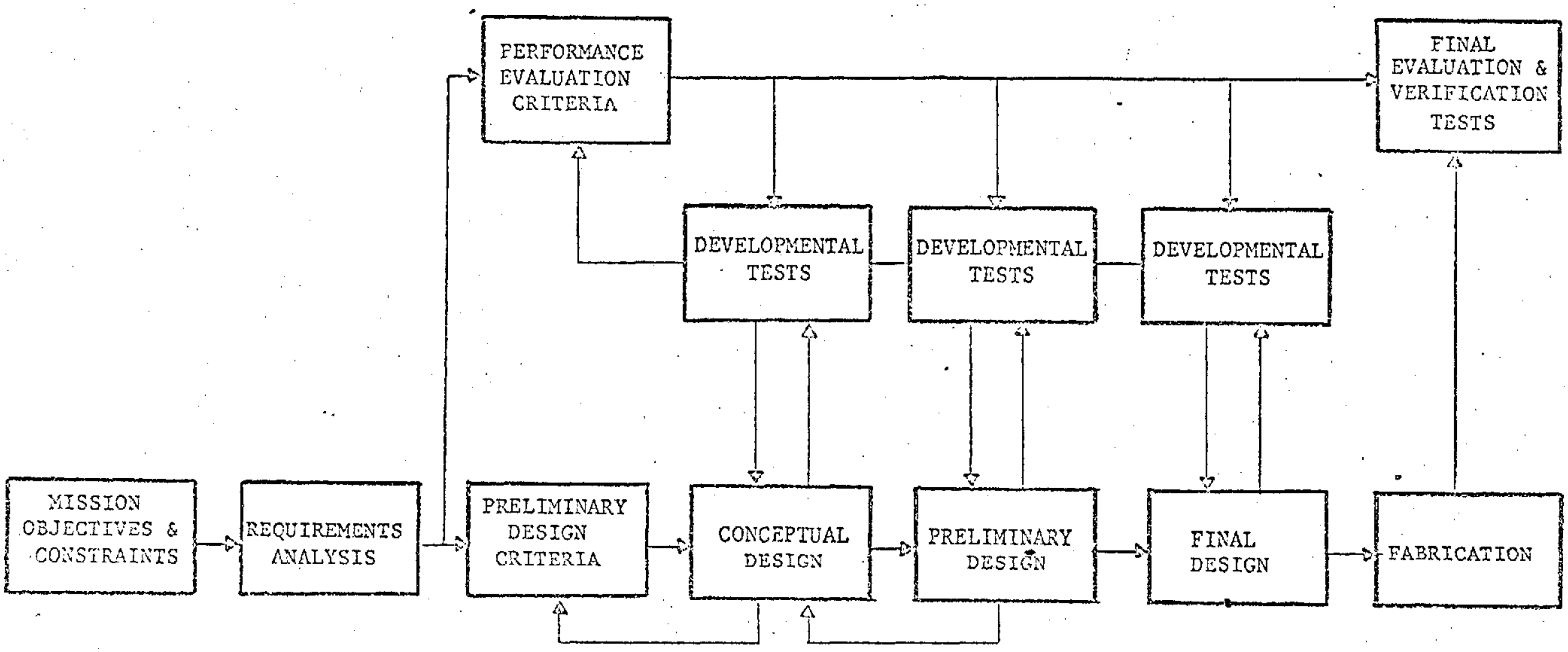

FIGURE 2. Role of Evaluation Criteria in the System Design and Development Cycle

TABLE 1. EVENT SCHEDULE

I. Manipulator System Laboratory

A. General Event Schedule

1. Appropriate task module placed on the task board and the hard wire leads connected to the readout and recording devices.
2. Lighting at the task site is set and calibrated.
3. Video links activated:
    - a. Experimenter's view of subject
    - b. Experimenter's view of a repeat of the task area
    - c. Subject's view of the task site with controls for:
        - i. FOV - zoom control - variable
        - ii. Pan and tilt controls - variable
        - iii. Focus control - variable
        - iv. Iris and sensitivity setting - fixed
4. Controller activated:
    - a. Limit indicators for each manipulator degree of freedom at subject's station
    - b. "Bundled" limit indicator at experimenter's station indicating some one D.O.F. is at its limit
5. Computer activated for both control and recording.
6. Subject seated, chair adjusted, controller adjusted and instructions read.
7. Technician on station in task area.
8. Computer manned.
9. Experimenter's station manned.

B. Task Area

1. Lighting -- Available studio lighting will be fixed by the experimenter before test. Provisions for adjusting light levels are made.
2. 2 cameras are available and they will be set up and calibrated by experimenter before testing.
3. A Research Technician who will have voice communication with experimenter will be stationed in the Task Area to do on-site recording.

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

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

C. Subject's Area

1. Controller

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

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

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

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

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

2. TV

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

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

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

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

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

C. Experimenter's Area

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

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

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

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

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

TABLE 2.

Relationship Between Mission Requirements and Selected Tests

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

TABLE 3. System and Performance Parameters

	MANIPULATOR TESTS				
SYSTEM/PERFORMANCE PARAMETERS	1 Terminal Kit Adaptor	2 Minimum Positional Change	3 Module Removal	4 Tip Position	5 Tip Orientation
Manipulator					
Configuration Accuracy	X		X		
Stability	X			X	
Drift		X		X	
Minimum Positional Change		X			
Actuator Power					
Orientation Accuracy	X	X			X
Straight Line Motion Accuracy	X		X		
Effector					
Dexterity	X				
Grip Retention Accuracy	X		X		
Time to Grasp	X		X		
Time to Modify Grip			X		
Effector Selection Accuracy	X				
Grip Force					
Worksite					
Force Limits			X		
Alignment Accuracy	X				
Control (Manipulator)					
Position Repeatability	X	X	X		
Rate Repeatability			X		
Force Repeatability			X		
Time to Initiate Control			X		X
Tip Placement Accuracy	X		X	X	
Orientation Accuracy	X		X		X
Anomaly Detection Accuracy					
Obstacle Detection Time					

TABLE 3, Continued

SYSTEM/PERFORMANCE PARAMETERS	MANIPULATOR TESTS 6 Dexterity	 7 Fasten Unfasten	 8 Distance Estimation	 9 Force-Torque	 10 Antenna Deploy
Manipulator					
Configuration Accuracy		X			X
Stability					
Drift					
Minimum Positional Change					
Actuator Power				X	
Orientation Accuracy	X	X			
Straight Line Motion Accuracy			X		X
Effector					
Dexterity	X	X			X
Grip Retention Accuracy		X			X
Time to Grasp		X			
Time to Modify Grip		X			X
Effector Selection Accuracy					
Grip Force				X	
Worksite					
Force Limits				X	
Alignment Accuracy		X	X		X
Control (Manipulator)					
Position Repeatability	X		X		
Rate Repeatability					
Time to Initiate Control		X			
Tip Placement Accuracy	X				
Orientation Accuracy	X	X			X
Anomaly Detection Accuracy			X		
Obstacle Detection Time			X		
Force Repeatability				X	X

2.4 Mobility System Evaluation Program

Several operator performance tests are planned for the MSFC Mobility System Laboratory. This facility was under construction during CY 1973 so that activities were constrained to test planning and specification of test hardware requirements. The mobility system facility consists of a specially poured and treated floor suitable for air bearing vehicle operations and two vehicles mounted on air bearing pads. The vehicles are a passive satellite model and a teleoperator model having a cold-gas propulsion system which is controlled from a remote station via a R-F data link.

The teleoperator model is capable of five degree-of-freedom motion. This includes translation in the horizontal plane and three attitude degrees-of-freedom. The operator controls the vehicle via an integrated hand controller which combines the five degrees-of-freedom. A television system is incorporated into the teleoperator model and closes the control loop. To preclude reception of invalid cues, the entire operating area is enclosed in black cloth of low reflectivity.

The main purpose of the mobility system facility is the testing of propulsion systems, propulsion control systems, and satellite/teleoperator interface hardware during closed loop maneuvering of the system by an operator. That is, while the visual system laboratory tests and the computation laboratory simulation discussed elsewhere in this report are chiefly oriented to the operator input interface, the mobility system program addresses the control or operator output side. The use of variable propulsion systems and variable control system dynamics permits study of effects of these parameters on operator control actions and, therefore, on system stability and maneuvering accuracy.

(1) General Test Objectives

During the satellite approach and docking phases of the teleoperator mission, the system operator will be required to exercise precise control of teleoperator position, attitude, and rates so as to follow a nominal course and range-range rate profile in the final approach. The mission functions conducted in the vicinity of the satellite (within 30 ft range) include:

- Station-keeping
- Satellite Inspection
- Final Approach
- Docking/Grappling

The test approach is to conduct man-in-the-loop simulation studies of these phases of the teleoperator mission and to collect system performance data under various conditions of:

- Satellite Characteristics
- Lighting
- Mobility/Control System Parameters
- Initial Teleoperator Dynamic State

The performance data will then provide figures of merit for decisions regarding mobility/control system design requirements. Operators will attempt to accomplish a particular mission task (such as final approach and docking) using appropriate controls and displays. Runs will be made according to a planned <u>run schedule</u> which will give the parameter levels for each run. This schedule will incorporate an experimental design providing data suitable for a statistical analysis of the effects of the various parameters on system performance.

(2) Test Planning

The current planning calls for three specific studies to be conducted during CY 1974.

Study 1 - Free Flyer Handling Qualities in Final Approach To and Docking With a Stable Satellite

The initial experiment will involve approach to and docking with a stable satellite. The mission will commence with the teleoperator model at an initial range of approximately 25 feet from the satellite model. The operator will attempt to close the range to the satellite in accordance with a planned range-range rate profile. During the final approach, the operator will control attitude and translation to null any angles or rates existing between the body axes of the vehicles. Finally, the operator will attempt to effect docking using a probe-drogue docking mechanism.

The independent variables to be manipulated in the initial test include the following:

- Direction of initial teleoperator velocity vector with respect to the satellite (up to 20°).
- Teleoperator initial velocity (up to 5 ft/sec).
- Teleoperator initial yaw (up to 5°).
- Incident illumination angle with respect to the satellite ($0\text{-}90^{\circ}$).
- Control system mode
    - Closed loop
    - Open loop
        - Single pulse
        - Pulse train

Since the number of combinations of levels of these variables is large, an attempt will be made to reduce the number of trials required by employing an experimental design having some higher-order interactions confounded with subjects. Several such designs have been worked out and will be available when testing begins. The requirements to use such a design are that all independent variables must have the same number of levels, where k is a prime number. Applying modular arithmetic to the variable level indexes then yields a design where the highest order interaction (or some other selected interaction) is partially confounded with individual differences between subjects. Sacrificing this information on one interaction reduces the total number of trials by a factor 1/k. The method permits exploration of the effects of a large number of independent variables with the minimum number of trials.

Study 2 - Station-Keeping At Constant Range

In the second mobility unit test, the operator will attempt to circumnavigate the satellite so as to permit inspection. The circumnavigation will be carried out nominally at a fixed range. This will require controlling the vehicle in a circular flight path which requires simultaneous two-axis control. The independent variables will include those planned for the first test. The results of the first test will also influence the selection of independent variables for the second test.

Study 3 - Station-Keeping At Variable Range

Study 3 involves circumnavigation of a satellite having appendages such as booms where the proper flight path is basically circular but requires range excursions to avoid satellite excursions.

Task 3 is, therefore, the most difficult of the three tests. From an analytic viewpoint, the tests progress in complexity from Test 1 to Test 3. In terms of nominal translation coordinates as functions of time, Test 1 requires that the operator produce a position ramp output. Test 2 involves position coordinates which are simple sinusoidal functions of time. Test 3 requires a complex sinusoidal output with fairly large position excursions.

In terms of orientation, or attitude, control difficulty also increases through the test series. In Test 1, attitude becomes critical near the end of the mission during final docking. Mission success is less influenced by attitude during the initial translation. Furthermore, the operator can use a strategy of separating attitude and translation control by first achieving the proper translation path and then making attitude corrections.

Tests 2 and 3, by contrast, require simultaneous control of attitude and translation or, at least, more rapid alternation of the operator's attention between the two.

Dependent Measures

The dependent measures to be employed parallel those being developed for the Computation Laboratory approach simulation. The classes of measures include:

- Completion time
    - Total mission
    - Mission segments
- Propellant consumption
    - Total mission
    - Mission segments
- Translation and attitude error statistics

The general approach to measuring position error statistics will be to develop a nominal flight path expressing a time history for each degree of freedom. The difference between the nominal and obtained time history values at any point in time then constitutes an error measure which may be integrated over time.

3.0 FFTO MISSION ANALYSIS

This section summarizes the effort expended by the Essex Corporation in performing the mission analysis in support of the free flying teleoperator flight experiment definition. The experiment definition study was being conducted by Bell Aerospace in 1972 and 1973 and this report constitutes the Essex input to that study.

The objectives of the mission analysis were: to provide NASA MSFC and Bell Aerospace with mission data for the flight experiment definition effort; to establish the applicability of the free flying teleoperator for shuttle and payload support missions; and to develop a justification for the free flying teleoperator to operationally support shuttle and payload missions.

Due to the fast changing nature of the world of the shuttle and shuttle payloads, it was decided that input data for this study must be as current as possible. For this reason, the study relied heavily on contacts with organizations currently involved in payload definition and requirement studies. These included payload personnel at NASA Headquarters and at all appropriate centers, as well as contacts with personnel involved in such requirements studies as the SOAR, TOPSS, and Low Cost Payloads (McDonnell-Douglas, North American Rockwell, and Lockheed respectively).

The primary input data to the study consisted of the 1972 NASA mission model and the associated payload Data Book prepared by the Aerospace Corporation in July of 1972. Based on information from these and specific payload sources, a data book for each payload in the model was developed. This set of data comprised the output data to be used in the flight experiment definition.

The applicability of the free flying teleoperator for shuttle and payload support missions was established using a five point rating scale denoting the degree of applicability and the source of the data used in establishing the ratings. The rating of five indicated that the FFTO is the only system capable of performing the specific support mission with the specific payload. Ratings of four and three meant that payload personnel had identified the use of the free flyer for the payload support mission, with four meaning that the FFTO had received strong support from these personnel, while a three meant that the payload people had identified the free flyer as one potential approach, among others. A rating of two indicated that no information relative to the use of the free flyer was obtained from payload personnel, however, no constraints on its use have been identified. Finally, a rating of one meant that the free flyer has no application. The results of the rating analysis over nine potential missions are presented in Table 4. Comparisons of the FFTO with other techniques of payload retrieval and servicing are presented in Tables 5 and 6 respectively.

The results of the FFTO applicability analysis were as follows:

* Payload nominal retrieved - FFTO applicable to 90% of the missions (36 of 40 payloads).

  The distribution of ratings is presented in Table 4.

Table 4

FFTO Applicability Ratings- Number of Payloads

	Mission								
Rating	Nominal Retrieval	Contingency Retrieval	Retrieval Support	Deploy. Support	Deploy. Support	Post Deploy Checkout	On Orbit Servicing	On Orbit Inspection	Experiment Support
5 - FFTO only method	14	14	16	0	17	17	13	13	0
4 - FFTO strong candidate	5	21	3	0	0	1	8	4	2
3 - FFTO a contender	1	4	9	0	1	18	21	23	2
2 - FFTO possible	16	17	24	0	38	21	21	23	13
1 - FFTO not applicable	4	4	8	68	4	3	0	0	0
TOTAL	40	60	60	68	60	60	63	63	17

Table 5

Comparison of Systems for P/L Servicing

Capability of Alternate Approaches

	Approach				
Servicing Require. & Capabilities	EVA-Unaided	EVA-Aided	IVA-Shirt-sleeves	AMS	FFTO
Cargo Transfer	Extremely limited	No problems	Limited	No problems	No problems
Mass Handling at servicing site	Limited	No problems given aids	Limited	No problems	No problems
Reach envelope accessibility	Requires handholds, etc.	Required docking mechanisms	Interior only	Limited by reach and configur.	No problems given P/L interface
Checkout capability	Limited by Safety Concerns	Safety Problems	Safety problems	No problems except reach constraints	No problems
System flexibility	Use of man-adaptable	Use of man-adaptable	Use of man-adaptable	Constrained by P/L Orientation	No problems
P/L design interface	Extensive-aids and special design	Attach points	Equipment layout	Attach points	Attach points
Effect on shuttle	Major - a critical mission	Major - a critical mission	Moderate - stabilization requirements	Moderate - ties up shuttle	Minimal - Orbiter can perform other missions
Effect on crew safety	Major	Major	Major	Moderate - P/L is attached to shuttle	Minimal if FFTO maintains "safe" distance
Effect on Operator Workload	Major	Major	Moderate - man must still move in zero g.	Moderate - work conducted close to shuttle	Minimal - work conducted at a remote site - man in shuttle

Table 6

Comparison of Systems for P/L Retrieval

Capabilities of Alternate Approaches

Retrieval Requirements and Required Capabilities	Attached Manipulator	Approach Strongback-Pallet	Shuttle Direct Dock	FFTO
Capture-P/L Dynamics	Limited to stable P.L	Stable - coop. P/L	Stable - coop. P/L	No limitations
P/L mass	No limit. up to 65,000 lb.	No limitations	Limited to P/L in excess of 1,000 lb.	Unlimited given propulsion
P/L Design Impact	Attach points	Dock mechanism	Dock device	Attach points
P/L Orbit	Shuttle only	Shuttle only	Shuttle only	Unlimited (with Tug)
P/L Orientation	limited by reach envel.	limited by dock device location	limited by shuttle orientation	unlimited
P/L Safing	limited by reach	no manip.- required Auto system - no backup	no manip.- Auto system no backup	unlimited with manipulator system
P/L emplacement into bay	No problem	No problem	No capability	No capability
Impact on crew safety	Impact hazards	Impact hazards	Impact hazards	No problem for P/L handoff to attached manip.
Crew workload	No problem	No problem	Fine control of shuttle	No problem
Effect on other shuttle mission	Ties up shuttle	Ties up shuttle	Ties up shuttle	No constraints
Effect of failed retrieval system	Major to catastrophic	Catastrophic	Catastrophic	Minor to major depending on range

- * Payload contingency retrieval - 93% (56 of 60 payloads)
- * Retrieval Support - 86% (52 of 60 payloads)
- * Payload Deployment - 0
- * Deployment Support - 93% (56 of 60 payloads)
- * Post Deploy Checkout - 95% (57 of 60 payloads)
- * On Orbit Servicing - 100% (63 of 63 payloads)
- * On Orbit Inspection - 100% (63 of 63 payloads)
- * Experiment Support - 100% (17 of 17 payloads)

The justification for the FFTO lies in its relative capability to perform payload support missions as compared with other alternate approaches. Based on these comparisons, it was concluded that the FFTO is a feasible and practical method for conducting shuttle and payload support missions since its use provides the shuttle with an added dimension of:

- * Effectiveness - There are some P/L support missions which can only be done or which can be optimally be done by the FFTO as compared with other approaches.
- * Efficiency - Use of the FFTO does not tie up the shuttle and enables conduct of simultaneous missions.
- * Economy - It is cheaper to propel the FFTO to a worksite in space than to fly the shuttle to that site.
- * Safety of operations - the man is always located in a safe environment. The FFTO always operates at a safe distance.
- * Flexibility of operations - The FFTO makes minimum demands on P/L and shuttle orientation and alignment. The FFTO represents a

general purpose tool which extends and enhances the capabilities of the shuttle and its crew.

* Impact on Payload Design - Requires only attach points and design for servicing.

Based on these considerations, it is concluded that the concept of using the FFTO to support shuttle payloads (and the shuttle itself) is feasible and, for some missions, is preferable over other candidate support systems.

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