NASA Technical Memorandum 104796

International Space Station Alpha Remote Manipulator System Workstation Controls Test Report

William A. Ehrenstrom
Patrick Forrester, Major, United States Army
Lyndon B. Johnson Space Center
Houston, Texas

Colin Swaney
Rockwell Space Operations Company

National Aeronautics and
Space Administration

ACKNOWLEDGMENTS

The authors of this report would like to thank the following individuals for their help in planning and conducting this test: Marc Garneau, Astronaut Office (CB); Jay Legendre and Carlos Sampaio, Crew Station Branch (SP3); Duane Johnson and Jim Arbet, Flight Robotics Systems Branch (ER3); Bill Mackey, Spar; and John Maris, Canadian Space Agency. Special thanks *are* extended to Cory Logan, Facilities Operations Branch (SP5), for his extensive help setting up and scheduling the Space Station Mockup and Trainer Facility Node Workstation.

This publication is available from the NASA Center for AeroSpace Information, 800 Elkridge Landing Road, Linthicum Heights, MD 21090-2934, (301) 621-0390.

SUMMARY

This report documents the results of an evaluation to determine control implementation requirements for the Space Station Remote Manipulator System (SSRMS) Workstation controls, specifically, whether hardware or software controls were required. The test was conducted in the Space Station Mockup and Trainer Facility in Building 9 at the Johnson Space Center, Houston, Texas, from 18 to 28 January 1994. Nine NASA astronauts and one Canadian Space Agency (CSA) astronaut participated in the test as operators. The CSA requested this evaluation to close outstanding review item discrepancies from the Work Package 2 Critical Design Review in support of Workstation development.

Previous Workstation development testing had determined the need for hardware controls for the emergency stop, brakes on/off, and some camera functions (pan, tilt, and zoom). This test continued the Workstation development by evaluating camera iris and focus, backup drive, latching end effector (LEE) release, and autosequence controls using several types of hardware and software implementations. The results of this test will be used to define specific requirements for the Workstation design.

The four control implementations were: on-screen baseline software controls (also referred to as "latch on/latch off" controls), on-screen active while pressed controls, hardware controls, and keypad controls. The operators evaluated the controls by performing five tasks, each with various control configurations. For each task, the order of testing was varied for each operator to eliminate biases. The tasks were camera operation, backup drive operation, simultaneous robotic and camera operation, LEE backup release, and autosequence control.

During camera control evaluations, the operators rated the hardware controls slightly higher than keypad controls, followed by active-while-pressed controls and software controls. The operators stated the "latch on/latch off" controls could indirectly be a safety hazard. The operators performed the task faster with fewer overshoots/undershoots and erroneous inputs with the hardware controls than with the software controls. The operators also performed the task faster with the keypad controls than with the software controls and faster with the hardware controls than with the active-while-pressed controls. It is recommended that "latch on/latch off" controls not be considered for cameras.

During backup drive tasks, the operators rated the hardware controls the highest, followed by active-while-pressed controls and software controls. The operators considered the "latch on/latch off" SSRMS controls unsafe. The operators performed the task faster with the hardware controls than with the active-while-pressed controls or software controls. There was no significant difference between the control implementations in the number of erroneous inputs or target box deviations. It is recommended that "latch on/latch off" controls not be considered for the SSRMS.

During simultaneous camera and robotic operations, the operators consistently rated the hardware backup drive controls "Design Acceptable" with all camera controls except for software. Half of the operators rated the software camera controls in the "Deficiencies Required Improvement" or "Design Unacceptable" range. One operator rated the active-while-pressed camera controls with active-while-pressed backup drive control unacceptable because the tasks could not be performed simultaneously. The operators performed the task significantly slower with the active-while-pressed backup drive controls than with either the hardware or software backup drive controls. There was no significant difference between the control implementations in the number of camera deviations and final joint angle data and it is recommended that backup drive controls be provided on a dedicated hardware panel.

During evaluation of the backup LEE release task, most operators rated all the implementations acceptable. There were significant differences in time to complete the task between some of the implementations, but these differences were attributed to the mechanization of the controls. One operator rated every implementation unacceptable because none of the controls were guarded. The consensus was that a single guarded hardware button was preferred. It was recommended that, whatever the implementation, it must be guarded to prevent accidental actuation.

During the autosequence task, the operators rated both autosequence implementations acceptable, except for the case when software camera controls were used and when software autosequence controls were used in conjunction with keypad camera controls. The point of resolution travel distance following the surprise pause command was significantly larger for the software autosequence controls. There were no erroneous inputs for either of the control implementations and it was recommended that autosequence controls be provided on a dedicated hardware control panel.

Generally, the operators preferred hardware controls although other control implementations were satisfactory and acceptable. The results of this evaluation should be coupled with further testing to positively influence the design of the Space Station robotics Workstation.

CONTENTS

TABLE OF CONTENTS
(continued)

TABLE OF CONTENTS
(continued)

Page

FIGURES

TABLE OF CONTENTS
(continued)

Page

TABLES

ACRONYMS

AWP	active-while-pressed (controls)
CRT	cathode ray tube
CPU	computer processing unit
CSA	Canadian Space Agency
EE	end effector
GRAF	Graphics Analysis Facility
HW	hardware (controls)
HW X 1	One hardware button latching end effector release procedure
HW X 2	Two hardware button latching end effector release procedure
JSC	Johnson Space Center
KP	keypad (controls)
LCD	liquid crystal display
LEE	latching end effector
NTSC	National Television Standards Committee
PLC	programmable logic controllers
POR	point of resolution
RGB	red/green/blue
SPDM	special purpose dexterous manipulator
SSMTF	Space Station Mockup and Trainer Facility
SSRMS	Space Station Remote Manipulator System
SW	software (controls)
SW X 1	One software button latching end effector release procedure
SW X 2	Two software button latching end effector release procedure

INTRODUCTION

The purpose of this test was to define some of the requirements for off-screen (i.e., hard switch) controls for the Robotic Workstation associated with Space Station Remote Manipulator System (SSRMS), Special Purpose Dexterous Manipulator (SPDM), and camera control functions. This test was requested by the Canadian Space Agency (CSA) to close out outstanding review item discrepancies from the Work Package 2 Critical Design Review in support of Workstation development. The test results will be used to define some of the Workstation configuration requirements for the International Space Station Program.

Previously, crew evaluations had been conducted by the Space Station Freedom Displays and Controls Mode Team to define the display (on-screen data and command) requirements to support robotic operations. These studies concluded that some hard switch controls were required to support robotics (emergency stop and brakes on/off controls); they also concluded that some camera operations on the Workstation could not be adequately accomplished using software (SW) controls (pan, tilt and zoom).[1,2] This test continued the assessment of the robotic and camera controls. Software and hardware (HW) implementations of several functions were evaluated to determine which type of implementation best supported robotic and camera operations. The specific controls which were evaluated included camera iris and focus controls, SSRMS backup drive controls, and autosequence controls.

This test was conducted from 18 to 28 January 1994. A total of ten 3-hour evaluations by nine NASA crew members and one representative of the Canadian Astronaut Program Office were completed in the Space Station Mockup and Trainer Facility (SSMTF) in Building 9, Johnson Space Center (JSC), Houston, Texas.

TEST METHODS

TEST OBJECTIVES

The primary objective of this test was to determine the functional requirements for off-screen (i.e., hard switch) controls for the Workstation to support robotic and camera control tasks. Three sets of controls were evaluated using both on-screen and off-screen implementations:

- camera controls
- SSRMS backup drive controls (forward, reverse, and stop; joint select; latching end effector (LEE) release; LEE open snares; and LEE retract latches)
- autosequence controls (resume, pause, and stop)

The results of this test include recommendations for implementation of camera and robotic controls using either hardware or software. The specific test objectives used to evaluate each control implementation were as follows:

---

[1]Prenger, Henk, On-Board Workstation Evaluation, Flight Crew Operations Directorate, Space Station Support Office, Station Operations Section, Jan. 1992.

[2]Prenger, Henk, Crew Operational Assessment of SSF Workstations, Flight Crew Operations Directorate, Station-Exploration Support Office, Station Operations Section, Apr. 1993.

- Determine which control implementations could be used by the crew to safely and effectively execute the tasks.
- Determine any differences in the crew's ability to execute the tasks using the various control implementations.
- Determine which control implementations the crew preferred to use in executing the tasks.

TEST EQUIPMENT

The SSMTF was located in Building 9NW of JSC and was part of the Mockup and Integration Laboratory. The SSMTF consisted of full-scale mockups of the habitable portions of the International Space Station configuration and selected part task trainers and systems. The Node Mockup and Workstation were used for this test. A detailed description of the test Workstation layout, display formats, and control implementations is presented in Appendix A.

TEST PROCEDURES

Scenario Description

The robotic Workstation controls were evaluated by accomplishing five tasks with various control configurations (hardware and software). These tasks included:

- camera operation
- backup drive operations
- simultaneous robotic and camera operations
- LEE release
- autosequence control

The tasks were chosen to provide a representative cross section of the types of tasks which could be expected during on-orbit Space Station operations, including off-nominal scenarios. Several other tasks were included during the test which were not part of the evaluation to provide a more realistic test environment. These were all accomplished using on-screen controls.

Assumptions

The actual hardware implementation for the Workstation was not finalized at the time of the test; consequently, the Workstation layout and ergonomics were not evaluated. This test was meant to only evaluate functional requirements for the robotic and camera controls. Specific test setup differences/issues included:

- The test Workstation setup used cathode ray tube (CRT) screens rather than liquid crystal displays (LCDs) planned for the Station.
- The display sizes, particularly the video display size, had not been determined for the Workstation. This was not considered a factor to this test.
- The configuration of the Workstation (dedicated workstation versus portable computers) had not been determined. Application of these test results to a portable Workstation may not be appropriate.
- Task procedures were accomplished using a hard copy checklist; an electronic procedure viewer, expected for use on the actual Space Station Workstation, was not available.

- The camera used for this evaluation was not a flight-representative camera. The camera was assumed to be representative for the purposes of evaluating the different control implementations.

The display formats and configurations for the Workstation had not been finalized at the time of the test. The displays used for this test were the last display formats under evaluation by the Space Station Freedom Program (see Appendix A for a description of the display formats). For the purpose of this test, it was assumed these displays were not a factor in the results.

The tasks selected for this test were considered representative of tasks expected during actual Space Station operations. An attempt was made to provide sufficiently difficult tasks to isolate operational problems with specific control implementations.

Actual system latency in the Workstation controls was unknown. This test attempted to keep the latency for both the hardware and software control implementations approximately equal.

Previous testing concluded baseline software camera controls for pan, tilt, and zoom were unacceptable. However, from a human factors testing standpoint, it was appropriate to keep all camera controls together. Consequently, when the iris and focus controls were tested using a specific control configuration, all camera control (including pan, tilt, and zoom) was performed using the same configuration.

Application of these test results to SPDM may not be completely appropriate. While there may be significant commonality between SSRMS and SPDM, some SPDM tasks may require a special evaluation to determine appropriate control implementations. This will have to be done during SPDM development.

Groundrules

A test familiarization briefing was given to all the operators before the start of testing. In addition, each operator was given a pre-brief before the start of each test session. Emphasis was placed on test objectives, evaluation criteria, and familiarization with the tasks and displays/ controls.

The Workstation layout/ergonomics and the display formats/configurations were not evaluated. This was stressed during the pre-test briefings. General comments about the Workstation were not solicited directly during the test; however, all comments made by the test operators were recorded and documented to help with completion of display and control design. In addition, each operator had an opportunity to record general Workstation comments in a post-test questionnaire. These comments are summarized in the Results and Analysis section of this report.

Control configurations were evaluated in a different order by each test operator to avoid bias. Control combinations for simultaneous robotic and camera operations were different for each operator to isolate problems with specific combinations.

Crew ratings and comments were collected following completion of each part task in the test. A modified Cooper-Harper type rating scale was used for the majority of the ratings. The scale and crew evaluation forms are presented in Appendix B. The operators were briefed about the use of the scale before the start of the test. Desired and adequate performance criteria were defined, pre-briefed and then re-briefed before the start of each rated task. Additional comments concerning crew preferences were collected following completion of all tasks.

Test Points

This test was accomplished in part tasks. The order of the procedures and control implementations was selected to minimize bias toward one implementation. The tasks accomplished during the evaluation are described in detail in the Results and Analysis section. Other tasks were accomplished to provide realism and familiarize the test operator with the robotic displays and controls; these were done using on-screen controls only, and were not evaluated. The test point matrix is provided in Figure C-1.

Four general types of controls were evaluated during the test. Each control implementation was not evaluated for every task. The baseline software controls were those which represented the last generation of software controls evaluated under the Space Station Freedom Program. These controls were "latch on/latch off." The operator would actuate the control by a momentary cursor selection of the appropriate software button. Active-while-pressed software controls differed from the baseline in that the appropriate software button had to be continuously activated by the cursor to operate the control. The control was deactivated when the cursor was released. Hardware controls for both robotic and camera controls used wafer and toggle switches to specify and operate the desired controls. These hardware controls were placed on panels patterned after the Space Shuttle control panels. Camera controls were also available on the computer keypad. Detailed descriptions of the specific switch implementations are provided in Appendix A.

TEST DATA

Performance Data

Performance data (e.g., time to accomplish, number of iterations to accomplish, and errors made while doing the task) were collected for each part task by a data collector (not the test conductor). Each task had specific parameters which were recorded; the parameters are specified in each test description in the Results and Analysis section.

Operator Ratings

The operators evaluated the control implementation following completion of each task. The rating scale for most tasks was a modified Cooper-Harper rating scale (Figure B-1). The desired and adequate performance criteria, made up of performance measures for each task, are described in the Results and Analysis section. Other tasks were rated acceptable or unacceptable. It should be noted that time to perform the task was not used as a criterion in the operator ratings.

Post-Test Ratings

At the completion of the test session, each operator completed a post-test questionnaire to summarize their comments about the Workstation control implementations. Operator preferences were also collected. The questionnaire is provided in Appendix B.

Crew Consensus Report

A Crew Consensus Report was provided by the Astronaut Office following completion of the test. The report provided the crew requirements, preferences, and associated rationale for each control implementation. This report is included in Appendix D.

TEST PLAN DEVIATIONS

Nine astronauts were originally planned for the test and the test point matrix was generated for nine test subjects. However, a representative of the Canadian Astronaut Program Office also participated. A new test point matrix was not generated; instead, test point set 8 was used twice.

The test checklist required the operators to perform a number of setup tasks before each actual data run. The intent was to familiarize the operator with the displays and provide a more realistic scenario. However, this unnecessarily lengthened the test without significantly improving it. Therefore, after it was clear the operator was comfortable with the displays, the data collector accomplished these setup tasks.

The backup drive back-away task required the movement of three different joints in a repeated sequence to perform the ungrapple. Each set of three movements was considered an iteration. Originally, the number of iterations required to perform the task was going to be measured as a performance criterion. However, since the operators were constrained as to where they could stop the movement of the end effector, there was no significant difference in the number of iterations between operators. These data were not used.

The time to accomplish the autosequence tasks was also originally planned as a performance criterion. However, partway through the test, it became apparent the definition of the time required was meaningless. Therefore, these data were collected but not used.

The test point flow presented in the test point matrix was adjusted for several operators to allow quicker completion of the test. In these situations, all control implementations for each task were accomplished consecutively, eliminating the need to perform the setup tasks. The order of the control implementations was preserved to minimize bias toward a single implementation.

RESULTS AND ANALYSIS

The tests were run as planned without significant deviation from the test plan. A summary of the test sessions is provided in Table C-2. In addition, all raw data collected during the test and the statistical methods used to analyze the data are summarized in Appendix C. Significant data are presented in graphical form in the text.

CAMERA CONTROL OPERATIONS

Test Description

The operator selected a "real" camera view using a camera available in the Building 9 high bay. The camera was initially positioned full right, level, fully zoomed out, focused to the full far setting, and iris fully closed. The test procedure required the operator to open the iris, pan/tilt to find a sign on the high bay floor, zoom the camera in on the sign, and then adjust the iris and focus to permit reading the sign. Following each task, the operator rated the specific control implementation.

Four types of controls were evaluated including: on-screen baseline software controls, on-screen active-while-pressed (AWP) controls, off-screen controls using a dedicated hardware control panel, and off-screen controls on the computer keypad.

The performance data collected during the test runs included:

- Time to Accomplish Task: The time was started when the operator selected the high bay camera to monitor. Time was stopped when the operator had a readable sign.
- Overshoots/Undershoots: During camera control tasks, if the operator stopped the camera (pan, tilt, zoom, focus, or iris) at a position which was other than the desired or intended position, an overshoot or undershoot was recorded. However, if the operator

intentionally paused at an intermediate position in order to systematically achieve the final desired position, it was not recorded as an undershoot.

- Erroneous Inputs: An erroneous input was defined as an input which resulted in an action other than intended such as activation of the wrong function switch or using the correct switch to move the camera in the wrong direction. Overshooting or undershooting the target was not considered an erroneous input.

In addition, crew ratings were taken at the conclusion of each camera control task using a modified Cooper-Harper rating scale. Operator performance was measured using the following criteria:

- Desired Performance: Achieve a readable image of the sign with no more than one overshoot/undershoot in each parameter.
- Adequate Performance: Achieve a readable image of the sign with no more than three overshoots/undershoots in each parameter.

Test Results

The time required to accomplish the camera control task using the various control implementations is presented in Table C-3 and is summarized below in Figure 1. The data show the hardware controls were significantly better than the software and active-while-pressed controls, i.e., the operators were able to accomplish the task more quickly using the hardware implementation. In addition, the keypad (KP) controls were significantly more efficient than the baseline software controls. Statistically, there was no significant difference between the hardware and keypad implementations nor between the software and active-while-pressed controls.

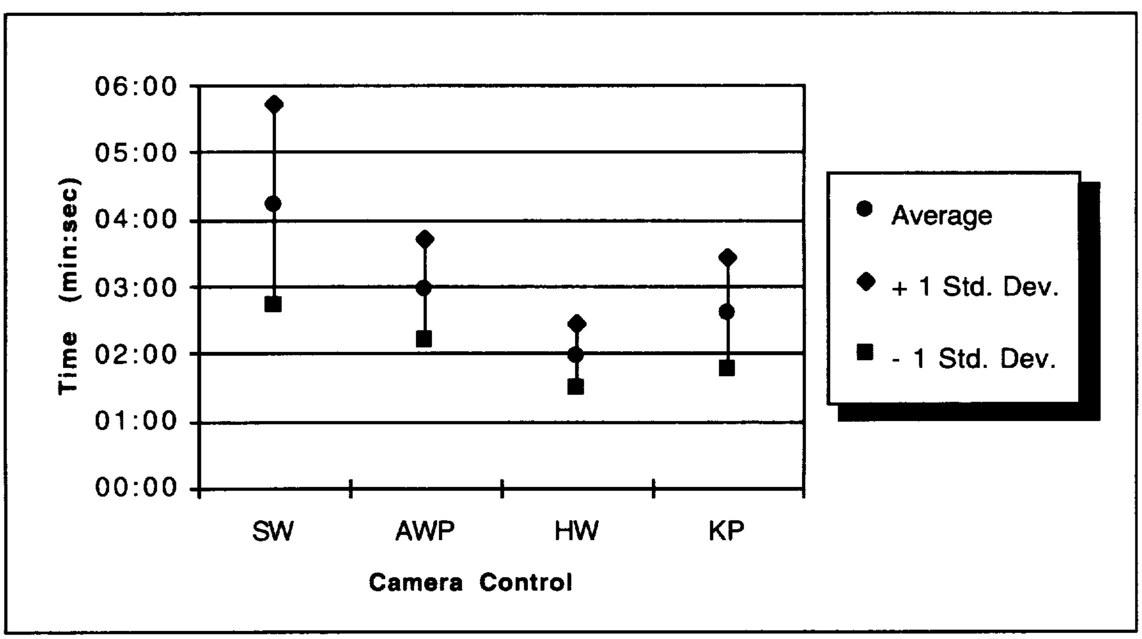


Figure 1: Task Completion Times for Various Camera Control Methods

Overshoot/undershoot data are presented in Table C-4 and are summarized below in Figure 2. There was a significant difference between the hardware and baseline software implementations. This signifies the operators were less likely to overshoot or undershoot the intended camera position using the hardware implementation. Statistically, there was no difference between the rest of the control implementations.

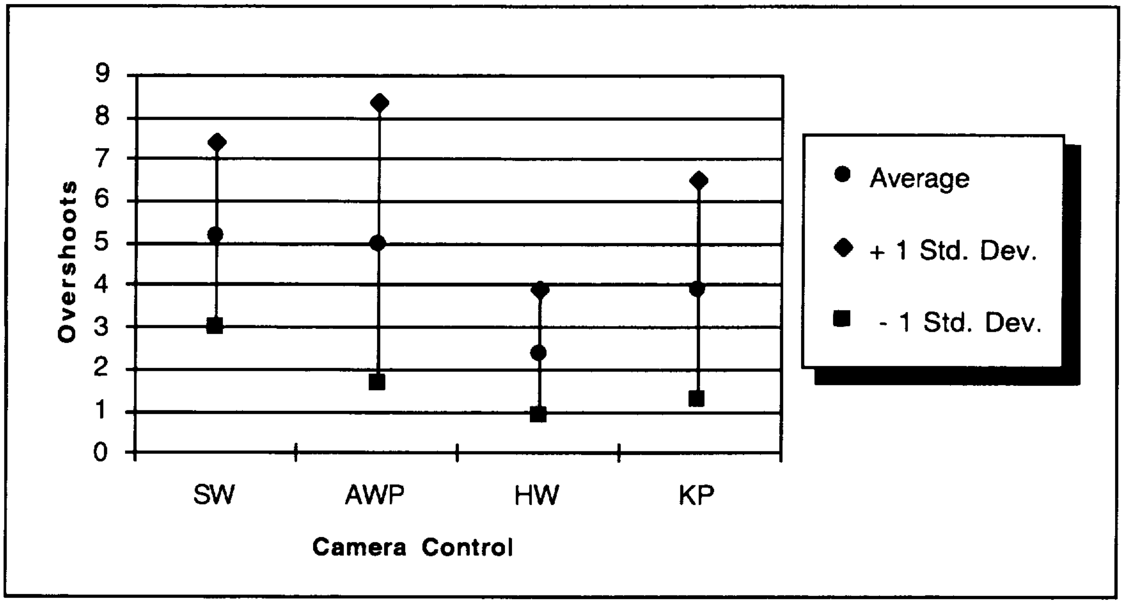


Figure 2: Total Overshoots/Undershoots for Various Camera Control Methods

The number of erroneous inputs performed by the crew is summarized in Table C-5. The hardware had the fewest errors although, statistically, there was difference only between the hardware and baseline software implementations.

The operator ratings using the modified Cooper-Harper scale are summarized below in Table 1. The results indicate only the hardware controls consistently fell within the "Design Acceptable" portion of the scale. The crew consensus report concluded the operators were able to accurately control the camera using the hardware and felt there would be a positive habit transfer from Orbiter camera controls due to the similarity. The one operator who rated the hardware implementation low (7) identified a problem with latency; this operator performed the camera task using the hardware controls first and this score may represent a task familiarization problem. The operators were able to consistently perform the task to the desired performance level using the keypad controls but most felt the controls required more concentration than they preferred. However, the crew consensus report indicates the keypad would be an acceptable alternative to the hardware controls. The baseline software controls were clearly unacceptable with half of the operators rating the controls within the "Deficiencies Require Improvement" portion of the scale. Comments indicated a potential safety problem with the "latch on/latch off" type of controls since these require a significant amount of concentration, potentially diverting attention from other more important tasks.

Table 1: Modified Cooper-Harper Ratings for Various Camera Control Methods

Camera Control	Modified Cooper-Harper Ratings 1	2	3	4	5	6	7	8	9	10
Hardware	1	2	4	2			1			
Keypad		1	3	6						
Active While Pressed			4	1	2	2		1		
Software				1	3	1	2	2		1

Conclusions

Overall, the operators preferred the hardware controls. They required less time and made fewer errors using the hardware controls than with the other control implementations, although statistically there was no difference between the hardware and keypad controls. The keypad controls were considered acceptable and were rated only slightly less desirable than the hardware controls. The baseline software controls were unacceptable. There was a significant degradation in the operators' ability to perform the tasks with the software controls. The operator comments indicated the "latch on/latch off" implementation could indirectly be a safety hazard. Do not consider "latch on/latch off" movement of the cameras. (R1)[3]

BACKUP DRIVE OPERATIONS

Test Description

The task was initialized with the SSRMS positioned over a grapple pin. The operator backed the end effector away from the grapple pin using backup drive controls. The primary task view was the tip end effector camera view. The test operator attempted to keep the grapple pin within the confines of an overlay box while performing the task. The task was completed when the end effector was approximately the length of the grapple pin above the top of the grapple pin. Following each task, the operator rated the specific control implementation.

Three control implementations were used to accomplish the tasks: on-screen baseline controls, on-screen active-while-pressed controls, and off-screen controls on a dedicated hardware panel (see Appendix A for a description of the control implementations).

The performance data collected during the test runs included:

- Time to Perform the Task: The time was started when the operator selected the first joint in the back-away sequence (shoulder yaw). The time was stopped when the test conductor determined the end effector was the required distance above the grapple pin. The test conductor rather than the operator made this determination to provide consistency in the data.
- Erroneous Inputs: An erroneous input was defined as the selection of the wrong joint or the wrong direction of movement.

---

[3]Numerals preceded by an R within parentheses at the end of a sentence correspond to the recommendation numbers tabulated in the Conclusions and Recommendations section of this report.

- Deviations From the Target Box: A deviation was recorded whenever the entire grapple pin base exited the target box. If any part of the pin was touching the target box lines, a deviation was not recorded.

In addition, crew ratings were taken at the conclusion of each backup drive control task using a modified Cooper-Harper rating scale. Operator performance was measured using the following criteria:

- Desired Performance: Backing away from the grapple pin without deviating from the target box and without an erroneous input for joint selection or direction of movement
- Adequate Performance: Backing away from the grapple pin with less than two deviations from the target box and with no more than one erroneous input for joint selection and direction of movement

Test Results

The time required to accomplish the back-away task using the various control implementations is presented in Table C-6 and is summarized below in Figure 3. The data indicate a significant difference between the efficiency of the operators to perform the task using the hardware controls compared to the baseline software and active-while-pressed controls.

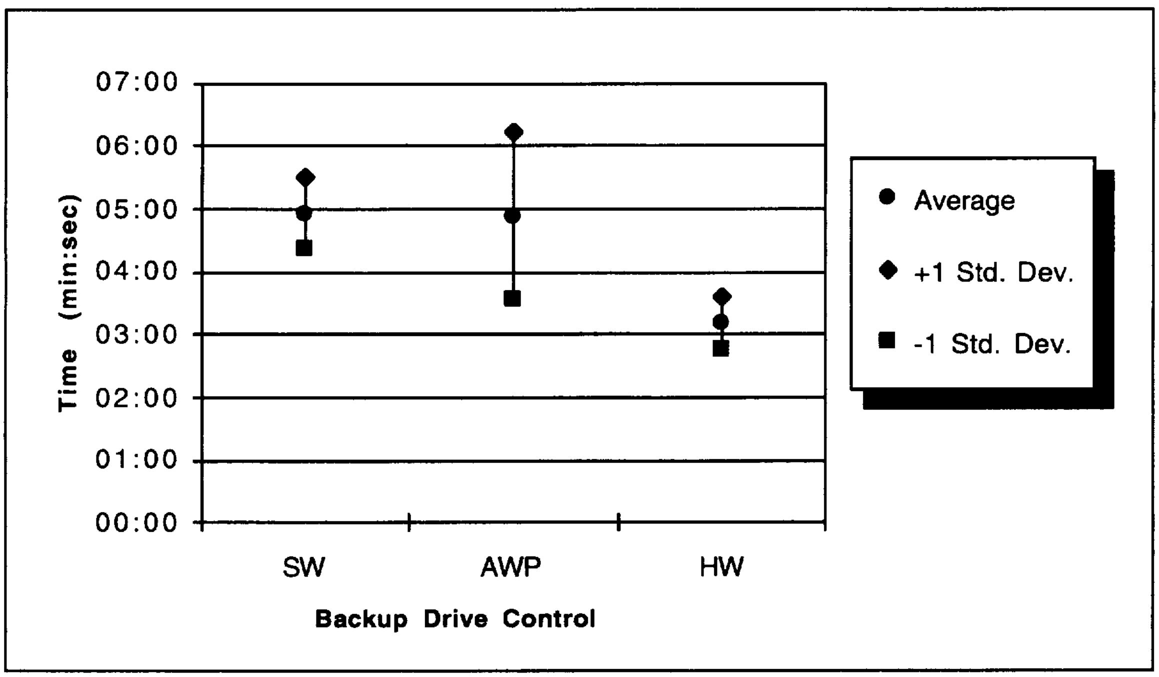


Figure 3: Task Completion Times for Various Backup Drive Control Methods

The erroneous input data, presented in Table C-7, does not show any significant difference between the control implementations. Baseline software data shows only one error amongst the operators (data from two of the operators were not available). Both hardware and active-while-pressed had a total of two errors for all the operators. The deviation from the target box data, presented in Table C-8, are similar. Statistically, there is no significant difference between the implementations.

The operator ratings, using the modified Cooper-Harper scale, are summarized below in Table 2. The results indicate both hardware and active-while-pressed controls were consistently rated in the "Design Acceptable" portion of the scale. The crew consensus report states that while the hardware controls were preferred, the active-while-pressed controls would be acceptable with modification from the test setup. In the test, the operators were required to select a joint and then select another button to move the joint. This was considered inefficient. They preferred the ability to perform both tasks (joint selection and movement) by actuating one button. The operators rated the baseline software controls unacceptable. The crew consensus report indicates the "latch on/latch off" feature is a safety hazard for these types of operations.

Table 2: Modified Cooper-Harper Ratings for Various Backup Drive Control Methods

Backup Drive Controls	**Modified Cooper-Harper Ratings**									
	1	2	3	4	5	6	7	8	9	10
Hardware	2	3	2	2		1				
Active While Pressed		3	4	1	2					
Software		1	1	1	2	2		1		2

Conclusions

Overall, the operators were able to perform the back away task most efficiently using the hardware controls. This was the operators' preferred implementation. The crew consensus report states the active-while-pressed controls could be made more efficient by eliminating the need to separately select a joint and then drive the joint. With this modification, active-while-pressed controls would be an acceptable alternative to the hardware controls. The baseline software controls were considered unsafe and therefore unacceptable due to the "latch on/latch off" feature. Do not consider "latch on/latch off" movement of the SSRMS. (R2)

SIMULTANEOUS BACKUP DRIVE AND CAMERA OPERATIONS

Test Description

After successfully backing away the end effector, the operator repositioned the SSRMS to a specific elbow pitch angle. During this reposition, the operator attempted to keep the end effector in the center of one of the camera views. Camera control was varied between operators using the different implementations specified in the Camera Control Operations section. All combinations of camera controls and backup drive controls (12 different combinations) were tested, although each operator evaluated only three combinations. The purpose of this task was to isolate problems which may not have been evident when operating the camera and backup drive controls separately. Following each iteration, the operator rated the specific control implementations.

The performance data collected during the test runs included:

- Time to Accomplish Task: Time was started when the operator selected the elbow pitch joint. Time was stopped when the operator stopped the joint at the desired pitch angle.
- Deviations of End Effector From Camera Center of View: A deviation was recorded whenever the center of the grapple fixture crosshair no longer overlaid the on-screen end effector view. If the crosshair center touched any part of the end effector, a deviation was not recorded.

- Final Joint Angle: The operator was required to stop the end effector at an elbow pitch angle of $120^\circ \pm 2^\circ$. The intent of this measure was to determine if a particular backup drive control implementation made it difficult to accurately position the SSRMS.

In addition, crew ratings were taken at the conclusion of each task using a modified Cooper-Harper rating scale. Operator performance was measured using the following criteria:

- Desired Performance: Stopping the elbow pitch joint within two degrees of target position. No more than one deviation while attempting to maintain the grapple fixture target crosshair on the end effector.
- Adequate Performance: Stopping the elbow pitch joint within three degrees of target position. No more than three deviations while attempting to maintain the grapple fixture target crosshair on the end effector.

Test Results

The time to accomplish the task data, using the various backup drive control and camera control combinations, are presented in Table C-9 and are summarized below in Figure 4. The data show a significant difference between the hardware and active-while-pressed and the baseline software and active-while-pressed controls. There was no significant difference between hardware and software. These results indicate active-while-pressed backup drive controls were inefficient when the operator was required to perform other tasks (such as camera control) simultaneously.

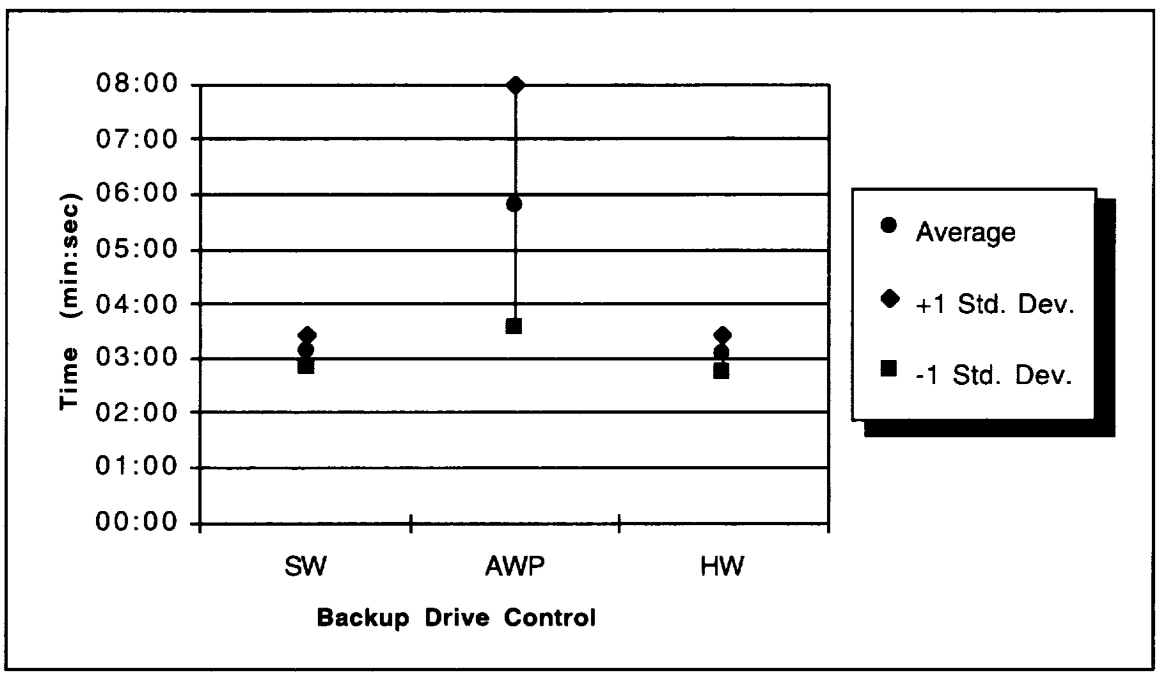


Figure 4: Task Completion Times for Simultaneous Backup Drive and Camera Operations

The camera deviations data are presented in Table C-10. Statistically, these data do not show any significant difference between the control implementations.

The final joint angle data are presented in Table C-11. The operators were consistently able to stop the joint within the desired limits. There is no significant difference between the data.

The operator ratings using the modified Cooper-Harper scale are summarized below in Table 3. Several results are evident upon close inspection. First, the hardware backup drive controls were consistently rated "Design Acceptable" with all camera controls except baseline software. Half of the operators rated the baseline software camera controls within the "deficiencies require improvement" or "Design Unacceptable" range of the scale, further emphasizing the operators' discomfort with that camera control implementation. One notable combination was the active-while-pressed camera controls in conjunction with the active-while-pressed backup drive controls. One operator rated the combination "Design Unacceptable" because of the inability to perform the tasks simultaneously. Because the cursor was required for both actions, the operators had to move the joint and camera incrementally. This was considered extremely inefficient.

Table 3: Modified Cooper-Harper Ratings for Simultaneous Backup Drive and Camera Control Operations

Camera Control	Backup Drive Control		
	Hardware	AWP	Software
Hardware	1,4	3,4,4,4	4,4
Keypad	2,3	4,6	3,4
AWP	2,3,3	4,10	4,4,5
Software	5,6,7	5,7	5,7,10

Conclusions

The operators stated the ability to perform camera and backup drive operations simultaneously was an important consideration for control implementation. In particular, support tasks such as camera control should not require long periods of dedicated attention. This was illustrated in the measured performance as well as the operator ratings. Overall, the hardware backup drive controls consistently allowed the operators to satisfactorily perform the task with any camera control except the baseline software. The baseline software camera controls required too much attention and were considered a significant distraction while attempting to perform the primary robotic control tasks. The use of the trackball for both the camera and backup drive tasks was considered inefficient. Active-while-pressed backup drive controls, while acceptable on their own, were significantly less efficient when camera control was simultaneously attempted. Provide backup drive controls on a dedicated hardware control panel. (R3)

LATCHING END EFFECTOR RELEASE OPERATIONS

Test Description

The task was initialized with the SSRMS connected to a grapple fixture. The scenario simulated an operator monitoring the end effector for malfunctions. If a malfunction was detected, the operator would release the end effector. A caution and warning event for an end effector mechanism malfunction was activated by the test conductor; the operator then responded with either a LEE Release or a LEE Retract Latch followed by a LEE Open Snare. Following each task, the operator rated the specific control implementation.

The task was accomplished four times using on-screen one-button (SW X 1) and two-button (SW X 2) procedures and off-screen one-button (HW X 1) and two-button (HW X 2) procedures. See Appendix A for a description of the control implementations.

The performance data collected during the test runs included:

- Time to Accomplish Task: Time was started when the caution and warning event was presented to the operator. Time was stopped when confirmation of the LEE release was presented.
- Erroneous Inputs: An erroneous input was defined as selection of the wrong button or the wrong sequence of buttons.

In addition, a crew assessment of the acceptability of the control implementations was taken at the end of each attempt. The rating was made in consideration of the number of erroneous inputs. Acceptability was measured using the following criteria:

- Acceptable: No erroneous inputs
- Unacceptable: One or more erroneous inputs

Test Results

The release time data are presented in Table C-12. All the release times are comparable. There is a significant difference between the two-button software and the one-button and two-button hardware implementations, but this was attributed to the control mechanization and not to operator response time. It should also be noted that the operators were permitted to preposition the cursor over the appropriate software control button when the baseline software configuration was evaluated. The response times may have been different if the operators had been required to search for and then properly position the cursor. There were no erroneous inputs for any of the operators using any of the control implementations. This may have also been affected by the ability to preposition the cursor over the appropriate software button before the task.

The operator ratings are summarized below in Table 4. One operator rated every control implementation unacceptable because none of the controls were guarded. This was considered a safety hazard. Guard emergency controls to prevent accidental actuation. (R4)

The only other unacceptable rating was due to the placement of the software two-button controls. Specifically, the RETRACT LATCH button was placed below the OPEN SNARE button even though it had to be actuated first. The operator felt this configuration was counter-intuitive and potentially a safety hazard.

Table 4: Ratings for Various LEE Release Control Methods

End Effector Release Controls	Acceptable	Unacceptable
HW X 1	9	1
HW X 2	9	1
SW X 1	9	1
SW X 2	8	2

Conclusions

There was no clear distinction in the results using the different implementations and all were acceptable given sufficient safeguards to prevent inadvertent actuation. The crew consensus was that a single guarded hardware button was preferred. However, a software configuration would also be acceptable if properly designed. Specifically, a software implementation should include a two-button procedure with the first button used to arm and the second to execute the release.

AUTOSEQUENCE OPERATIONS

Test Description

The task was to initiate, monitor, and control an autosequence. The SSRMS was initialized to the autosequence start point. The autosequence had two intermediate, preprogrammed pause points and an end point. To maneuver to the first pause point, the operator initiated the autosequence and then simply monitored the movement of the SSRMS. To maneuver to the second pause point, the operator resumed the autosequence, manually paused at a pre-briefed arm position, and then restarted the autosequence. During the maneuver to the end point, the test conductor asked the operator to manually pause the autosequence; this was not known to the operator prior to this point. The operator then restarted the sequence to complete the task. During the autosequence, the operator tracked the SSRMS in two camera views (simultaneous robotic and camera operations); camera control was varied between operators using the different implementations specified in the Camera Control Operations section. Following completion of the autosequence task, the operator rated the specific control implementations.

Two control implementations were evaluated: on-screen baseline and off-screen controls on a dedicated hardware panel (see Appendix A for a description of the control implementations).

The performance data collected during the test runs included:

- Erroneous Inputs: An erroneous input was defined as the selection of the wrong button or actuation sequence.
- Point of Resolution (POR) Distance for Surprise Manual Pause: This distance was defined as the POR travel from the time the test conductor requested the operator to pause the autosequence to the time the arm stopped moving.

In addition, a crew assessment of the acceptability of the control implementations was taken at the end of each attempt. The rating was made in consideration of the number of erroneous inputs. Acceptability was measured using the following criteria:

- Acceptable: No erroneous inputs
- Unacceptable: One or more erroneous inputs

Test Results

There were no erroneous inputs during any of the autosequence test runs.

The data on POR distance traveled following a surprise manual pause are presented in Table C-13 and are summarized in Figure 5. The data show a significant degradation in the operators' ability to quickly pause the autosequence using the baseline software implementation compared to the hardware controls. This was due to the requirement to locate the cursor, position it over the PAUSE button, and actuate the control. This was considered a safety hazard for situations where an unexpected event requires a rapid pause.

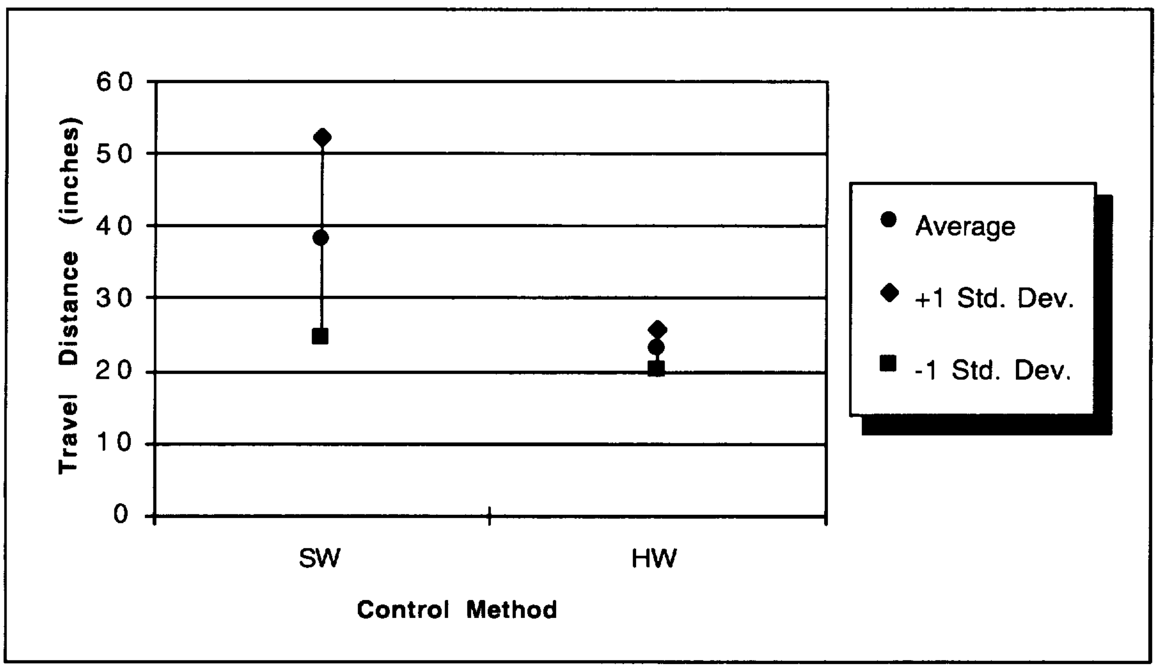


Figure 5: Point of Resolution Travel Following Surprise Manual Pause

The operator ratings are summarized below in Table 5. In general, both autosequence controls were acceptable except in the case where baseline software camera controls were used; these unacceptable ratings were attributed to the camera controls alone. The only other unacceptable rating was a software autosequence control with keypad camera controls. In this case the operator specifically mentioned the need to move the cursor from the camera display to the autosequence action area to perform the pause. This was considered a safety hazard due to the time required to perform the task.

Table 5: Ratings for Autosequence Controls Methods

Camera Controls	Autosequence Controls			
	Hardware		Software	
	Acceptable	Unacceptable	Acceptable	Unacceptable
Hardware	3		2	
Keypad	2		3	1
Active While Pressed	2		1	
Software	1	2	1	1

Conclusions

The hardware controls were the preferred autosequence controls, although the crew consensus report states the baseline software controls were acceptable. However, the POR travel during surprise manual pause indicated a significant degradation in performance using the baseline software controls. This control implementation required more time for access and activation resulting in increased arm travel distances following the surprise manual pause command. This was considered a safety hazard for situations which require a rapid pause due to an unexpected event. Provide autosequence controls on a dedicated hardware control panel. (R5)

OTHER FINDINGS

General comments about the Workstation configuration and displays were recorded during the test sessions, in post-test questionnaires, and in the crew consensus report. While evaluation of Workstation ergonomics was not a specific objective of the test, these comments indicated areas of concern which should be addressed in the evolution of the Workstation design.

- System Latency: An attempt was made to minimize the effect of system latency in this test and an effort was made to equalize the latency for each control implementation. However, the effect of latency can have a dramatic effect on the ability of the operator to perform tasks with tight tolerances. A review of previous Workstation testing indicates minimal testing has been performed to determine acceptable limits for latency. Accomplish testing to determine the maximum acceptable system latency for SSRMS tasks. (R6)
- Malfunction Alert: During intensive robotic tasks, a malfunction may be overlooked if it is indicated only by a message on a display. Another means should exist to get the operator's attention when a malfunction occurs. Implement an audio malfunction alert. (R7)
- Control Redundancy: In most tasks evaluated during the test, the operators preferred the use of hardware over software controls. However, the operators indicated the desire for backup software controls in addition to hardware controls to provide redundancy in the event of hardware control malfunction.
- Workstation Hardware Configuration:
  - The brake switch on the hardware control panel should have talkback capability in addition to the on-screen indication.
  - The order of the displays was not intuitive and caused delays in executing the checklist. The numbering should be top to bottom and left to right.

- The camera control panel should be positioned so that the operator's arms do not block the displays while operating the cameras.
- The keyboard and the trackball should be transportable. The trackball should be capable of being gripped or being attached to the keyboard as needed.
- The trackball used in the test was too sensitive.

- Camera and SSRMS Controls:
  - The number of simultaneous tasks which will be required during robotic operations (robotic control, camera control, lighting, and systems monitoring) indicate the need to reduce operator workload. Investigate alternative camera control techniques. (R8)
  - The ability to change speeds (course/vernier) during both camera and robotic movement should exist.
- Display Configurations:
  - Controls and system monitoring displays should be grouped together in the primary work area to shorten the operational paths, reduce operator response time, and optimize operator crosscheck.
  - Talkback to indicate which controls are currently engaged is required for all on-screen controls.
  - The active area used for switch actuation should be enlarged.
  - All references to joint movement should be "+" and "-" rather than "FORWARD" and "REVERSE."
  - Color coding status changes would make them more recognizable. This has also been identified in previous testing.[4]

CONCLUSIONS AND RECOMMENDATIONS

Four camera control implementations were evaluated: on-screen baseline software controls, on-screen active-while-pressed controls, hardware controls on a dedicated control panel, and computer keypad controls. The hardware controls were the preferred method of camera control. Keypad controls were also acceptable. The baseline software "latch on/latch off" method of control was identified as unacceptable throughout the test.

R1. Do not consider "latch on/latch off" movement of the cameras. (Page 8)

Three backup drive control implementations were evaluated: on-screen baseline software controls, on-screen active-while-pressed controls, and hardware controls on a dedicated control panel. The hardware controls were the most efficient and the preferred control implementation. The operators indicated active-while-pressed controls would be acceptable if modified; however, active-while-pressed controls were significantly less efficient when combined with camera

[4]Testa, Andrew, Joint Angle Display Test, Engineering Directorate, Flight Robotics Systems Branch, in review.

operations. The baseline software controls were considered unsafe and therefore unacceptable due to the "latch on/latch off" feature.

R2. Do not consider "latch on/latch off" movement of the SSRMS. (Page 11)

R3. Provide backup drive controls on a dedicated hardware control panel. (Page 13)

Four LEE release control implementations were evaluated: one- and two-button baseline software and one- and two-button hardware controls. While the operators rated all implementations acceptable, they identified a potential safety hazard with all the implementations; specifically, the switches were open to unwanted actuation. They recommended two particular implementations which should be pursued to eliminate this hazard: a single, guarded hardware switch implementation or a two-button (ARM and RELEASE) software implementation. The two-button software activation would meet the requirement of a guarded switch.

R4. Guard emergency controls to prevent accidental actuation. (Page 14)

Two autosequence control implementations were evaluated: baseline software and hardware controls. Both control implementations were rated acceptable by the operators. However, the software implementation showed significant problems with the operators' ability to respond to a time-critical task.

R5. Provide autosequence controls on a dedicated hardware control panel. (Page 17)

While not a specific objective of this evaluation, comments were collected about the test Workstation configuration and display formats. These comments should be addressed in the evolution of the Workstation design. The primary recommendations are discussed below.

System latency may have a dramatic effect on the operators' ability to perform tasks with tight tolerances; however, little testing has been accomplished to determine acceptable system latency levels for SSRMS tasks.

R6. Accomplish testing to determine the maximum acceptable system latency for SSRMS tasks. (Page 17)

The operator workload during SSRMS operations may cause the operator to overlook a malfunction warning if indicated only by a message on the display. A means of directing the operator's attention to a malfunction should be implemented.

R7. Implement an audio malfunction alert. (Page 17)

When an operator is required to perform simultaneous tasks (robotic and camera), the increased workload prevents optimum results. Methods to reduce operator workload are needed.

R8. Investigate alternative camera control techniques. (Page 17)

REFERENCES

1. Prenger, Henk, On-Board Workstation Evaluation, Flight Crew Operations Directorate, Space Station Support Office, Station Operations Section, Jan. 1992.

2. Prenger, Henk, Crew Operational Assessment of SSF Workstations, Flight Crew Operations Directorate, Station-Exploration Support Office, Station Operations Section, Apr. 1993.

3. Testa, Andrew, Joint Angle Display Test, Engineering Directorate, Flight Robotics Systems Branch, in review.

4. Cooper, George E. and Harper, Robert P. Jr. The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities. Washington D.C.: NASA TN D-5153, April, 1969.

5. Holman, J.P. and Gajda, W.J. Experimental Methods for Engineers. 4th ed. New York: McGraw-Hill Book Company, 1984.

6. Avallone, Eugene A. and Baumeister, Theodore, eds. Marks' Standard Handbook for Mechanical Engineers. 9th ed. New York: McGraw-Hill Book Company, 1987.

APPENDIX A

SPACE STATION MOCKUP AND TRAINER FACILITY WORKSTATION DESCRIPTION

WORKSTATION CONFIGURATION

TEST HARDWARE

Node Workstation

The Node Workstation was configured as shown in Figure A-1. It had three 1024 X 768-pixel, 14-inch diagonal monitors which gave a true 14-inch diagonal active image. The displays were designated Display 1, 2, and 3 as shown in the figure. The monitors and video hardware and software supported X-windows operations on the three displays with mouse tracking across all displays. The Workstation used UNIX running on an Intel 486 computer processing unit (CPU). Red/green/blue (RGB) Spectrum boxes were used to give National Television Standard Committee (NTSC) overlays on all three monitors.

Two control panels were provided for the hardware camera and robotic control evaluations in this test. These control panels are shown in Figures A-2 and A- 3, respectively.

All hard switches and hand controllers were connected to Allen-Bradley Programmable Logic Controllers. These controllers performed signal processing and logic operations and read and write information to the Space Station Mockup and Trainer Facility (SSMTF) shared database.

Previous testing had determined the requirement for certain off-screen controls. These controls were provided in this study so that there was a representative high fidelity human-computer interface for the crew evaluation. These controls included the emergency stop switch and the brakes on/off switch.

Camera

The Building 9 high bay camera was used for testing camera controls. This camera was mounted above the tourist walkway and gave a plan view of the mockups. It was controllable from the Workstation and was selected because of its pan, tilt, focus, iris, and zoom control capabilities.

TEST SOFTWARE

Robotic Workstation

The basic screen, camera control, and camera stringing displays were developed by the Space Station Reconfiguration Office (DP4). The SSRMS displays were developed by the Canadian Space Agency (CSA)/Spar and implemented by ER3. All displays were built from the SAMMI version 2.1 format editor and run in the SAMMI V 2.1 runtime environment. Examples of the primary displays used for this test are presented below.

Application programs connected SAMMI displays and soft switches to the SSMTF shared database. Ladder logic programs connected the hard switches to the shared database. Robotics displays and soft controls were connected through an applications interface to software which generated joint angles from hand controller or display input. This software also interpreted display logic and control information. The database was polled by the Graphics Analysis Facility (GRAF) and SSMTF Programmable Logic Controller and transferred information when a change occurred. This information was used to control GRAF simulated cameras and robotics and SSMTF cameras and controls.

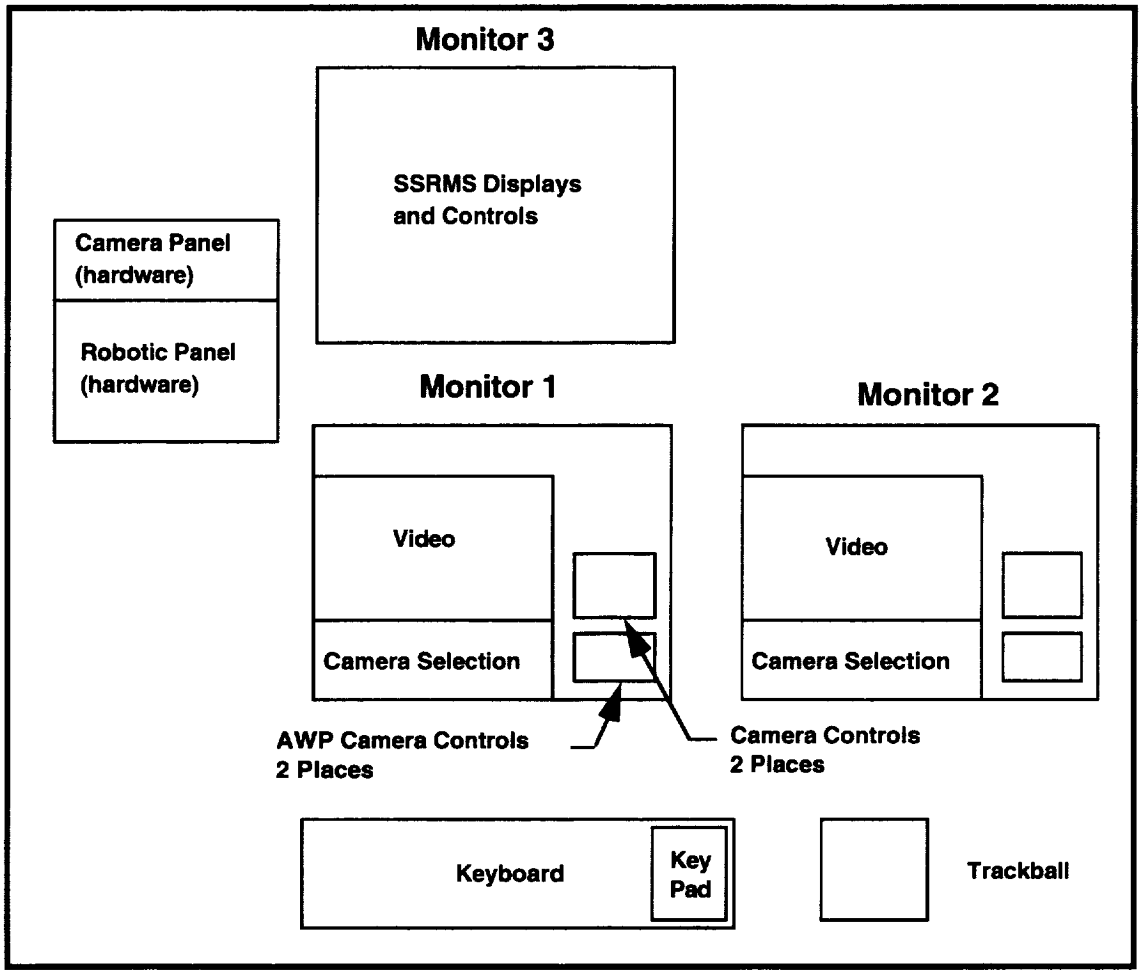


Figure A-1: Node Workstation Configuration

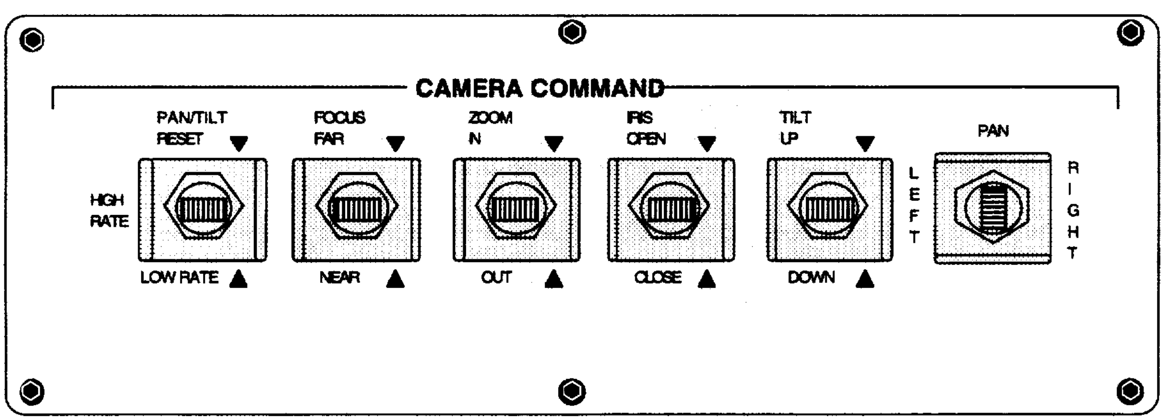


Figure A-2: Hardware Camera Control Panel

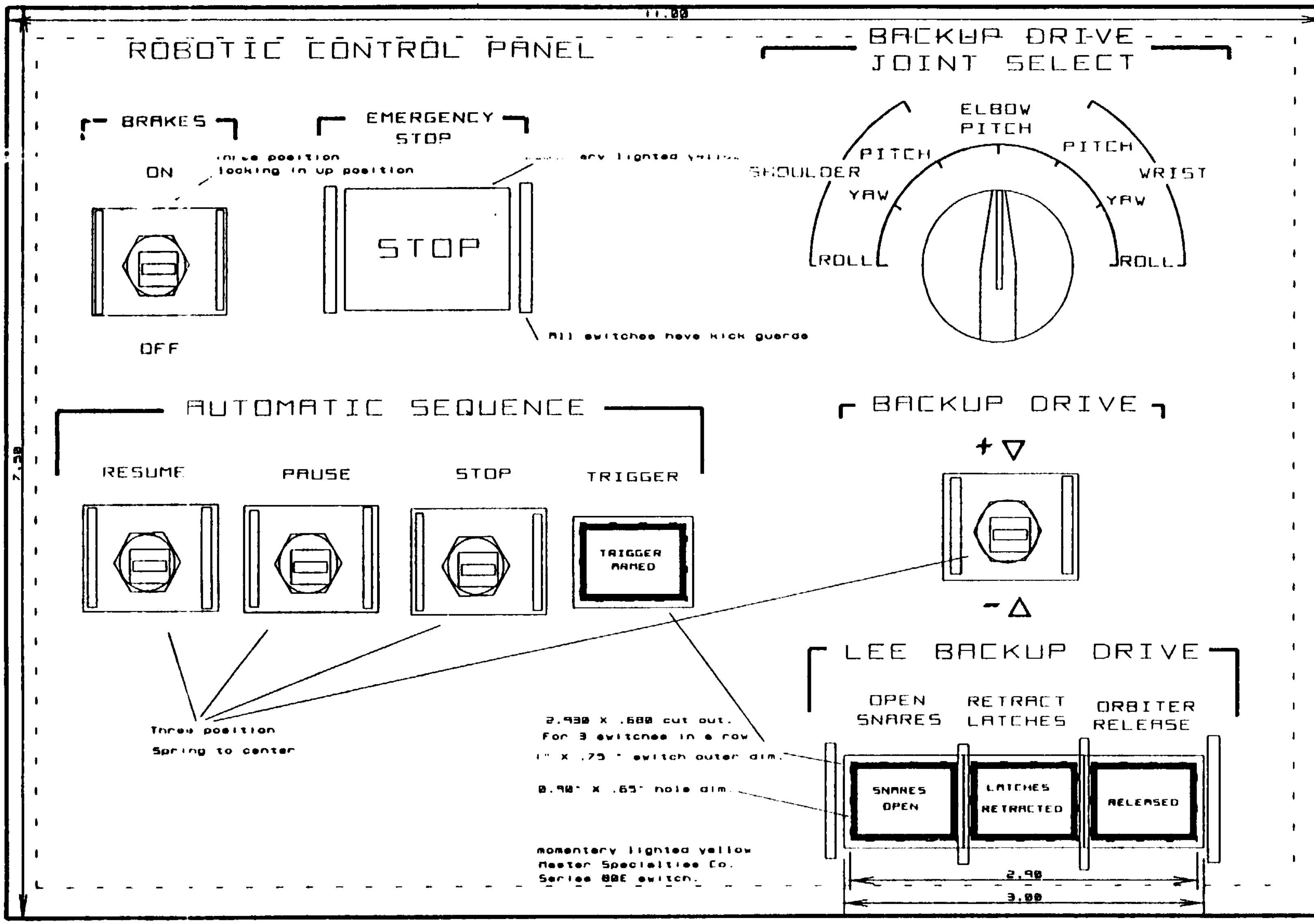


Figure A-3: Hardware Robotic Control Panel

Simulated Video

The GRAF was located in Building 15 and had RGB and NTSC computer video connections to the SSMTF. This facility specialized in geometric modeling and was used for the camera and robotic simulations shown in the SSMTF.

RGB Spectrum Model 2050 hardware was used to display NTSC video overlays on RGB Video. The source for NTSC video was a facility video router connected to the active facility cameras and simulated images generated on Silicon Graphics computers located in the Building 15 GRAF.

Simulated images of the various Space Station camera positions were generated in the GRAF upon command from the SSMTF shared database. This database was connected through software to the various control techniques used in the test. The GRAF computers polled this database and redrew the image from the perspective requested. These images were connected to the SSMTF Workstation through the video router. Robotic movement was generated from joint angle changes in the database. The GRAF received joint angle information from the SSMTF and redrew the camera image with the new joint information. Refresh time was approximately 200 milliseconds.

The simulated cameras had pan, tilt, and zoom control and the facility cameras had pan, tilt, zoom, focus, and iris control. Camera control was available through the keyboard keys, hard toggle switches, and computer graphical controls.

WORKSTATION DISPLAYS

SSRMS BACKUP DRIVE CONTROLS

The software backup drive controls were provided on the "rms_operate" display (Figure A-4). This display was selected using the BACKUP>> button on the "MSS Control Screens" menu or in the General Action Button area of any display. The specific use of the backup drive controls are described in Workstation Controls section.

SSRMS AUTOSEQUENCE CONTROLS

The software autosequence controls were provided on a separate "rms_operate" display (Figure A-5). This display was selected by selection of the OPERATE>> button on the "MSS Control Screens" menu or in the General Action Button area of any display. To use the autosequence, both the "POR . . ." and the "AUTO . . ." buttons were selected to bring up the correct autosequence control windows. Next, "POR AUTO . . ." was selected to bring up a Coordinate Frames window. The appropriate coordinate frames and autosequence were selected and then the window was hidden. The autosequence could then be performed using the controls described in Workstation Controls section.

CAMERA CONTROLS

Camera controls were available on the "CTS_ku_and_s_band controls" display (Figure A-6). To control a particular camera, the following steps were performed. First, the "SPLIT SCREEN . . ." button was selected revealing a window for the three available monitors. Next, the desired cameras were selected from the menu below the video window and assigned to the appropriate monitor. The video display to be controlled was selected with the cursor by designating any point in the lower half of the video display. The camera could then be controlled as described in the Workstation Controls section.

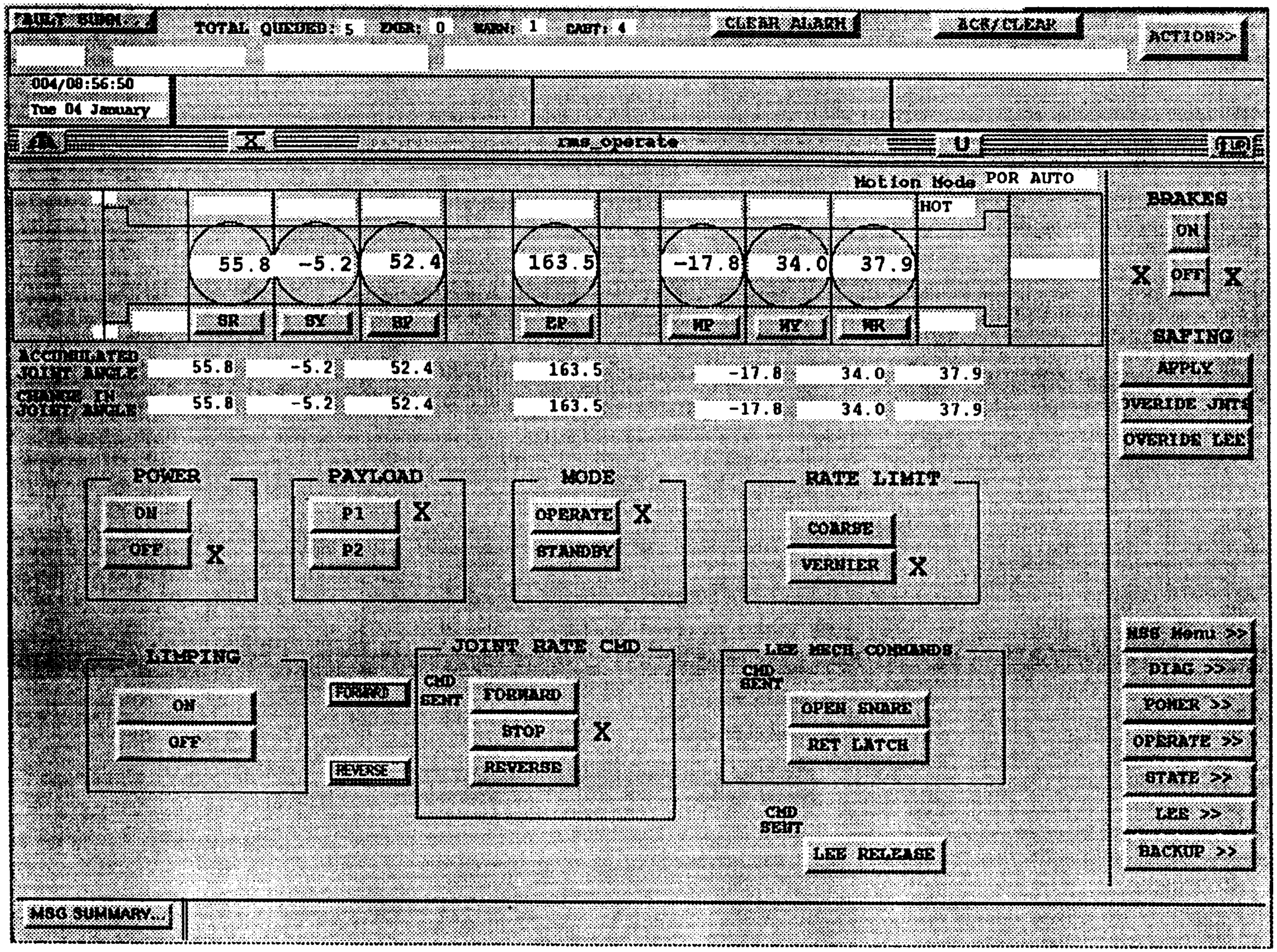


Figure A-4: Backup Drive Control Display

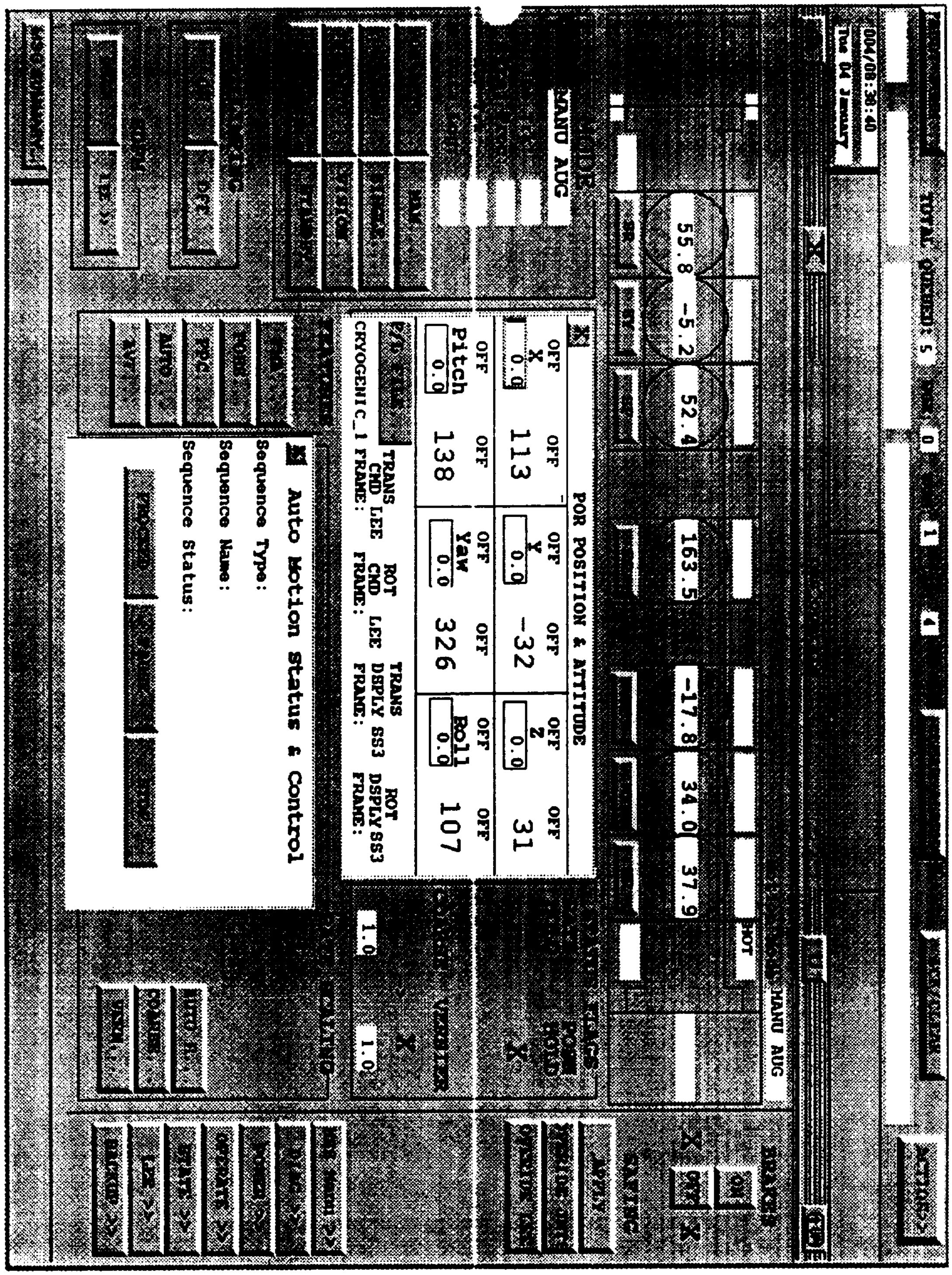


Figure A-5: Autosequence Control Display

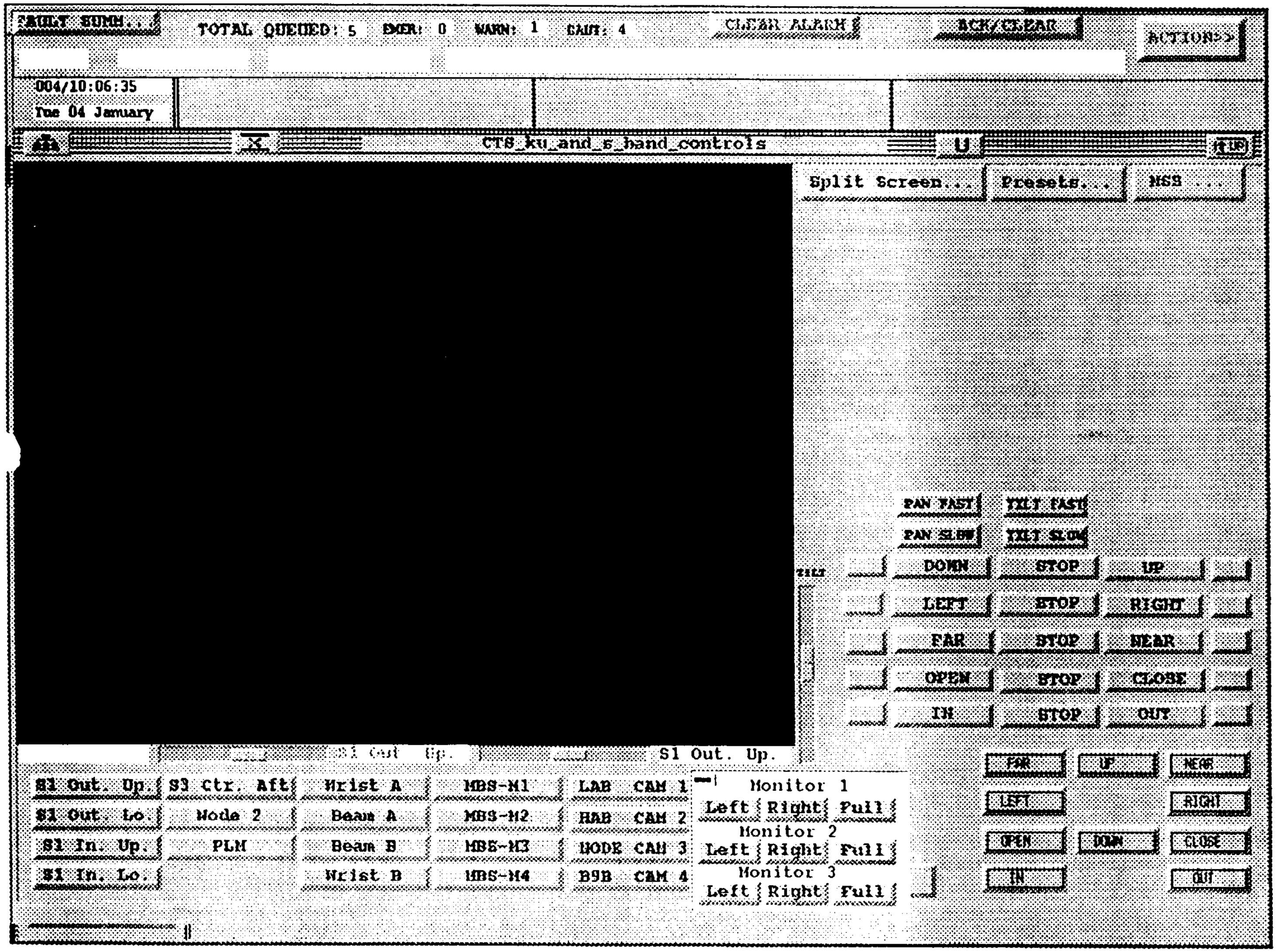


Figure A-6: Camera Control Display

WORKSTATION CONTROLS

Four general types of controls were evaluated during the test. The baseline software controls were those which represented the last generation of software controls being evaluated under the Space Station Freedom Program. These were "latch on/latch off" controls — the operator would turn on and off the control by a momentary cursor selection of the appropriate software button. Active-while-pressed software controls differed from the baseline in that the appropriate software button had to be continuously selected by the cursor to operate the control. The control was deactivated when the cursor was released. Hardware controls for both robotic and camera controls used wafer and toggle switches to specify and operate the desired controls. These hardware panels were patterned after the Space Shuttle control panels. In addition, camera controls were available via the computer keypad. Detailed descriptions of the specific switch implementations are provided below.

CAMERA CONTROLS

Software Baseline Camera Controls

The baseline camera controls provided pan (left/right), tilt (up/down), zoom (in/out), iris (open/close), and focus (near/far) control (Figure A-7). These controls were provided in the lower right corner of the “CTS ku- and s-band controls” display. When the operator clicked on a button to operate the camera, the camera would continue to operate as selected until it reached a hard stop or the operator clicked on the associated stop button. The small buttons on either side of the camera controls provided incremental pulse control. For example, a click on the small button the left of the pan left button will pan the camera to the left a small amount. The PAN FAST and PAN SLOW buttons were used to set the rates for pan camera operations. The TILT FAST and TILT SLOW buttons were not functional for this test.

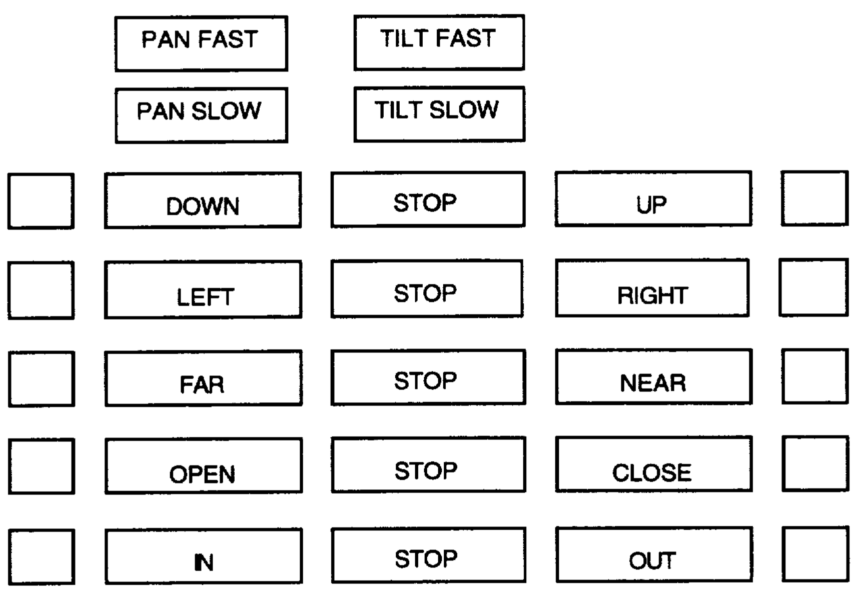


Figure A-7: Baseline Software Camera Controls

On-Screen Active-While-Pressed Camera Controls

The camera active-while-pressed controls (Figure A-8) were beneath the baseline camera controls on the "CTS ku and s-band controls" display and provided pan, tilt, zoom, iris, and focus control. When the operator clicked and held an active-while-pressed button, the camera continued to respond to the command until it reached a hard stop or the operator released the button.

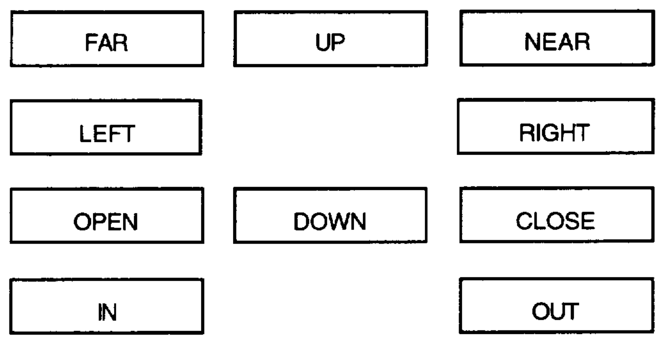


Figure A-8: Active-While-Pressed Camera Controls

Keypad Camera Controls

The keypad camera controls (Figure A-9) provided pan, tilt, zoom, iris, and focus control. Table A-1 lists the specific functions for each key. A keypad overlay was provided to clearly delineate functions to the operators. The camera continued to respond to the command until it reached a hard stop or the operator released the button. To use the keypad controls, the cursor arrow had to remain on the lower half of the video view of the camera being controlled.

Hardware Camera Controls

The hardware camera controls consisted of six toggle switches that provided pan, tilt, zoom, focus, iris, and pan/tilt speed select control (Figure A-3). The toggle switches, except for the pan/tilt speed select switch, were three-position, spring-to-center switches, with a center null position. The speed select switch was a three-position locking switch. The bottom position provided low rate control, the center position provided high rate control, and the top position was a reset. All the switches were oriented vertically, except for the pan switch, which was oriented horizontally.

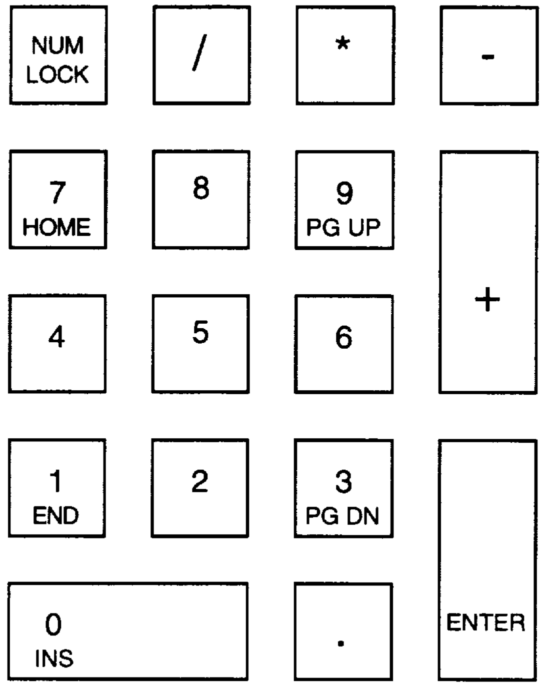


Figure A-9: Keypad Camera Controls

Table A-1: Keypad Camera Control Functions

KEY	FUNCTION
7	Focus Far
9	Focus New
8	Tilt Up
2	Tilt Down
4	Pan Left
6	Pan Right
1	Iris Open
3	Iris Closed
0	Zoom In
.	Zoom Out

BACKUP DRIVE JOINT CONTROLS

Baseline Software Backup Drive Controls

The backup drive provided single joint control for the SSRMS. The baseline software backup drive controls, within the JOINT RATE CMD box (Figure A-10), were in the lower portion of the "rms_operate" display. The operator selected the joint to be driven by clicking the button under the desired joint on the SSRMS schematic. Once the operator had selected the joint, the word SELECTED appeared above the joint. The operator then clicked on either the forward or reverse button to drive the joint in the positive or negative direction. The joint continued to move in the commanded direction until the operator clicked on the stop button.

Software Active-While-Pressed Backup Drive Controls

The software active-while-pressed backup drive controls were provided to the left of the baseline backup drive controls (Figure A-10) on the "rms_operate" display. The operator used the procedure outlined above to select the specific joint to be driven. The active-while-pressed backup drive controls provided forward and reverse joint control. When the operator clicked and held either active-while-pressed button, the joint continued to respond to the command until the operator released the button or a hard stop was reached.

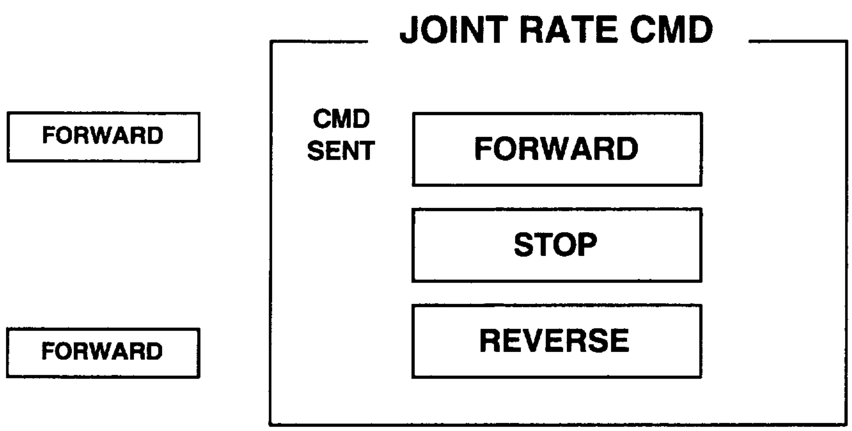


Figure A-10: Software (Baseline and Active-While-Pressed) Backup Drive Controls

Hardware Backup Drive Controls

The hardware backup controls were provided on the hardware robotic control panel (Figure A-2). The operator selected the joint to be driven by turning the rotary switch to the desired joint. The operator drove the joint in the positive or negative direction by moving the backup drive toggle switch up or down, respectively. The back up drive toggle switch was a three-position, spring-to-center switch, with a center null position.

BACKUP DRIVE RELEASE CONTROLS

Software Backup Drive Latching End Effector (LEE) Release Controls

The on-screen backup drive LEE release controls (Figure A-11) were in the lower right corner of the "rms_operate" display. Two LEE release methods were implemented. For the first method, the operator clicked on the RETRACT LATCHES button and then clicked on the OPEN SNARES button. For the second method, the operator simply clicked on the LEE RELEASE button.

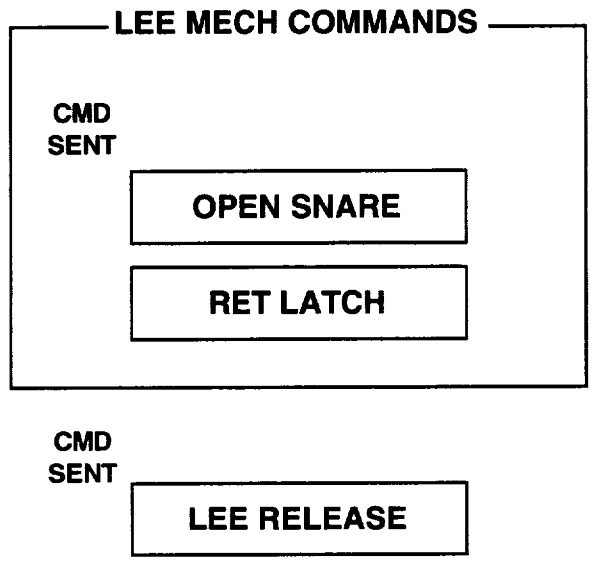


Figure A-11: Software Latching End Effector Release Controls

Hardware Backup Drive LEE Release Controls

The LEE backup release controls (Figure A-12) were on the lower right corner of the robotic control panel. Two LEE release methods were implemented. For the first method, the operator pushed the RETRACT LATCHES push button until the LATCHES RELEASED light was on steady and then pushed the OPEN SNARES push button until the SNARES OPEN light was on steady. The RELEASED button would illuminate after successful completion of the procedure. For the second method, the operator simply pushed the ORBITER RELEASE push button until the RELEASED light was on steady. The LATCHES RETRACTED and SNARES OPEN lights would illuminate sequentially to indicate successful completion of those tasks prior to release.

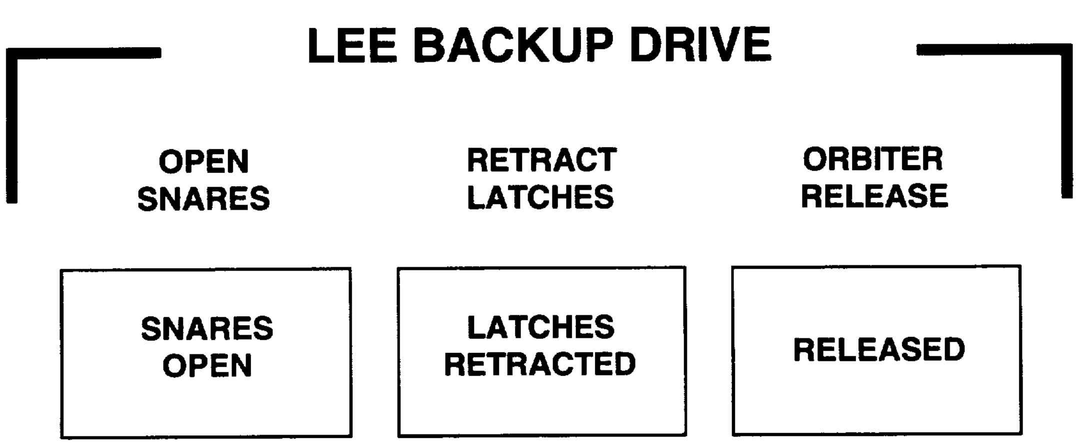


Figure A-12: Hardware Latching End Effector Release Controls

AUTOSEQUENCE CONTROLS

Software Autosequence Controls

Before entering the autosequence mode, the operator selected the translation display coordinate system, rotation display coordinate system, and autosequence identification. The on-screen autosequence controls consisted of PROCEED, PAUSE, and STOP buttons (Figure A-13). The operator clicked on the PAUSE button to pause an autosequence. The operator clicked on the PROCEED button to resume an autosequence that had been paused. The operator clicked on the STOP button to terminate an autosequence. To initiate or "trigger" motion at the start of an autosequence or after an autosequence had been resumed, the operator pushed the TRIGGER button on the hardware robotic control panel (see Hardware Autosequence Controls below). To issue the command, the operator depressed the TRIGGER button until the light was on continuously.

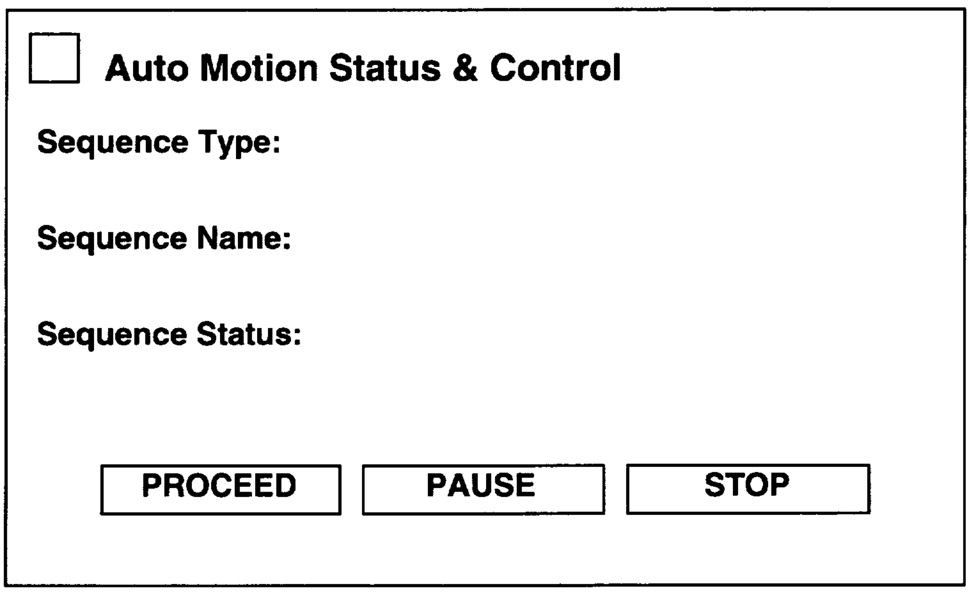


Figure A-13: Software Autosequence Controls

Hardware Autosequence Controls

The hardware autosequence controls were on the left side of the robotic panel (Figure A-14). The autosequence controls consisted of three-position, spring-to-center toggle switches, with a center null position. The toggle switches were used to pause, resume, and stop an autosequence. In addition to the toggle switches, there was a push button that was used to initiate or "trigger" motion at the start of an autosequence or after an autosequence had been resumed. To issue the command, the operator had to depress the button until the light was on continuously.

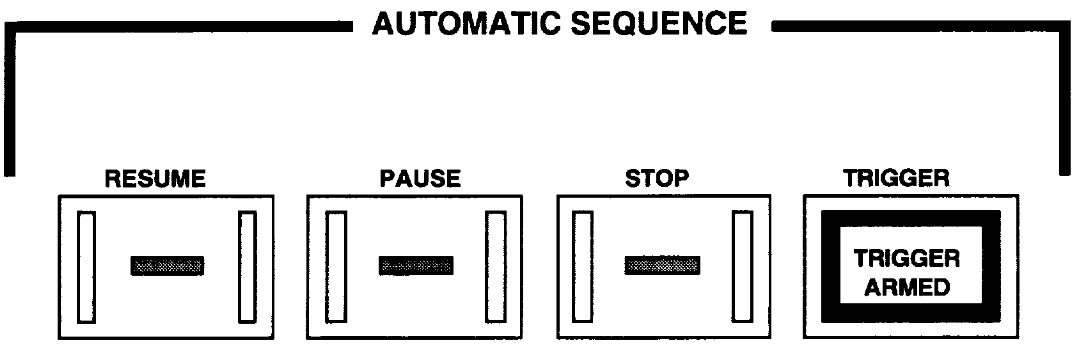


Figure A-14: Hardware Autosequence Controls

Hardware Brake Controls

The hardware brake control (not tested in this evaluation) was a two-position, locking toggle switch. The up position corresponded to brakes on and the down position corresponded to brakes off.

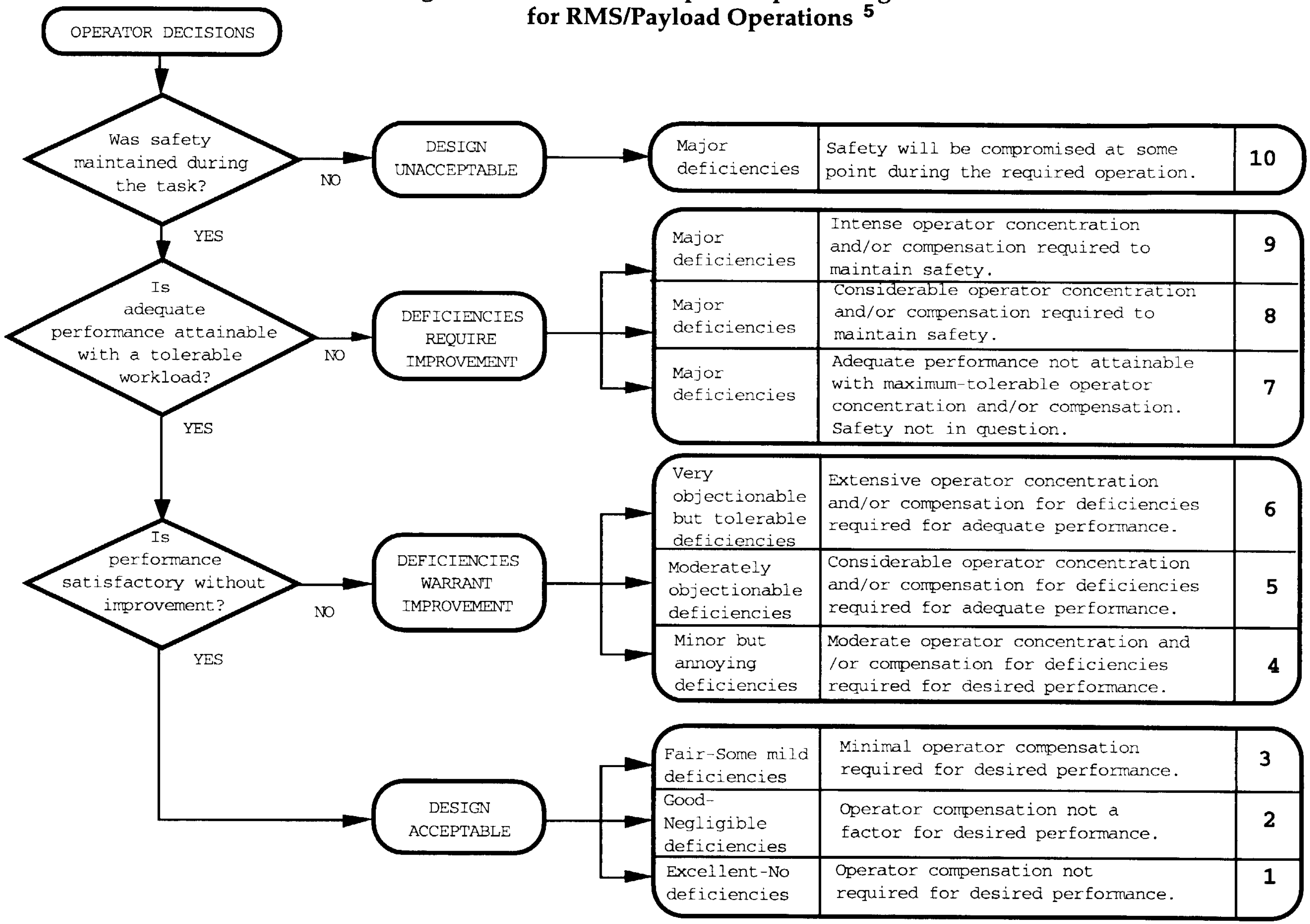
Emergency Stop Hardware Controls

The emergency stop controls (not used or tested in this evaluation) consisted of a single push button. The operator would use this control to stop the arm in an emergency.

APPENDIX B

CREW EVALUATION FORMS

Figure B1: Modified Cooper-Harper Rating Scale for RMS/Payload Operations [5]



[5] This scale was adapted from the flying qualities rating scale developed by George Cooper and Robert Harper Jr. and documented in NASA TN D-5153 The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities, April 1969. This modified scale has been used extensively in man-in-the-loop robotic testing at Johnson Space Center, Houston, TX.

POST-TASK COMMENT SHEET

TASK: Camera control

CONTROL: ________

DEFINITIONS:

Desired Performance: Achieve a readable image of the sign with no more than one overshoot in each parameter.

Adequate Performance: Achieve a readable image of the sign with no more than three overshoots in each parameter.

Valid Input: The camera operates as requested.

Erroneous Input: An input which results in an action other than intended. This could be activation of the wrong function switch or using the correct switch to move the camera in the wrong direction. Overshooting the target is not an erroneous input.

MODIFIED COOPER-HARPER RATING: ________

QUESTIONS:

1. Do you feel there are any safety implications with this implementation? YES/NO
   If yes, please comment:

2. Were you able to accurately interpret all camera control commands? YES/NO
   If no, please comment:

3. Did you ever doubt your ability to accurately control the camera during the task? YES/NO
   If yes, please comment:

COMMENTS:

1. General:

2. Screen/Hardware Configuration:

Time: _________ Input Errors: _____

Overshoots: Iris______ Focus ______ Pan ______ Tilt ______ Zoom ______

POST-TASK COMMENT SHEET

TASK: End effector release

CONTROL: ________

DEFINITIONS:

Acceptable: No erroneous inputs

Unacceptable: One or more erroneous inputs

Erroneous Input: Selection of wrong button or wrong sequence of buttons

ACCEPTABLE: ________ **UNACCEPTABLE:** ________

QUESTIONS:

1. Do you feel there are any safety implications with this implementation? YES/NO
   If yes, please comment:

2. Did situational awareness allow for quick identification and actuation of controls? YES/NO
   If no, please comment:

3. Was positive feedback (feel/talkback) available during switch actuation? YES/NO
   If no, please comment:

COMMENTS:

1. General:

2. Screen/Hardware Configuration:

Time: _________ Input Errors: ________

POST-TASK COMMENT SHEET

TASK: Back end effector off grapple pin

BACKUP DRIVE CONTROL: _________

DEFINITIONS:

Desired Performance: Backing off from the grapple pin without deviating from the target box and without an erroneous input for joint selection or direction of movement

Adequate Performance: Backing off from the grapple pin with less than two deviations from the target box and with no more than one erroneous input for joint selection and direction of movement

Erroneous Input: Selection of wrong joint or direction of movement

Iteration: The sequence of the three inputs (one movement of each of the three joints in the desired direction)

MODIFIED COOPER-HARPER RATING: ___________

QUESTIONS:

1. Do you feel there are any safety implications with this implementation? YES/NO
   If yes, please comment:

2. Did situational awareness allow for quick identification and actuation of controls? YES/NO
   If no, please comment:

3. Was positive feedback (feel/talkback) available during switch actuation? YES/NO
   If no, please comment:

4. Was anticipation (i.e. compensation) required to complete task within standards? YES/NO
   If yes, please comment:

COMMENTS:

1. General:

2. Screen/Hardware Configuration:

Time: _________ Iterations: _______ Input Errors: _______ Deviations: _______

POST-TASK COMMENT SHEET

TASK: Track end effector and stop motion during elbow joint reposition

BACKUP DRIVE CONTROL: ________ **CAMERA CONTROL:** ________

DEFINITIONS:

<u>Desired Performance</u>: Stopping the elbow pitch joint within two degrees of target position. No more than one deviation while attempting to maintain the grapple fixture target crosshair on the end effector.

<u>Adequate Performance</u>: Stopping the elbow pitch joint within three degrees of target position. No more than three deviations while attempting to maintain the grapple fixture target crosshair on the end effector.

MODIFIED COOPER-HARPER RATING: ________

QUESTIONS:

1. Do you feel there are any safety implications with this implementation? YES/NO
   If yes, please comment:

2. Were you able to quickly and accurately input the stop command? YES/NO
   If no, please comment:

COMMENTS:

1. General:

2. Screen/Hardware Configuration:

Time: ________ Deviations: ________ Final EP Setting: ________

POST-TASK COMMENT SHEET

TASK: Autosequence

AUTOSEQUENCE CONTROLS: ________ **CAMERA CONTROLS**: ________

DEFINITIONS:

Acceptable: No erroneous inputs

Unacceptable: One or more erroneous inputs

Erroneous Input: Selection of wrong button or actuation sequence

ACCEPTABLE: ________ **UNACCEPTABLE**: ________

QUESTIONS:

1. Do you feel there are any safety implications with this implementation? YES/NO
   If yes, please comment:

2. Did situational awareness allow for quick identification and actuation of controls? YES/NO
   If no, please comment:

3. Was positive feedback (feel/talkback) available during switch actuation? YES/NO
   If no, please comment:

COMMENTS:

1. General:

2. Screen/Hardware Configuration:

Time: ________ Input Errors: ________ Paused Joint Angles: ________ ________

POST-TEST QUESTIONNAIRE

TEST RESULTS:

1. Which switch implementation do you prefer and why?

   a. Camera Controls (select one):

      Baseline Software   AWP Software   Hardware Panel   Keypad

   b. LEE Release Controls (select one):

      SW (1 switch)   SW (2 switch)   HW (1 switch)   HW (2 switch)

   c. Backup Drive Controls (select one):

      Baseline Software   AWP Software   Hardware Panel

   d. Autosequence Controls (select one):

      Software   Hardware

2. Are there any controls which should have <u>both</u> software and hardware controls included on the Workstation? If so, why?

3. Based on your preference of control implementations, do you have any recommendations for screen/display layout or hardware topography (if not already discussed on task comment sheets)?

4. Do you think that a combination of software and hardware controls is the proper configuration for the Workstation?

5. Other comments (use back, if necessary):

TEST CONDUCT:

1. Were there any portions of the test that you were unclear about?

2. Was the pre-brief adequate for the test?

3. Do you have any suggestions to improve the test?

   a. Test procedures:

   b. Test location:

   c. Test equipment/implementation:

   d. General:

APPENDIX C

TEST DATA

TEST SUMMARY

Table C-1: Test Point Matrix

TASK	OPERATOR 1	2	3	4	5	6	7	8	9
Power Up (6.3.2.1)	SW (#1)	SW (#1)	SW (#1)	SW (#1)	SW (#1)	SW (#1)	SW (#1)	SW (#1)	SW (#1)
Camera Controls (6.3.2.2)	HW (#4)	SW (#2)	AWP (#3)	Keypad (#5)	Keypad (#5)	SW (#2)	AWP (#3)	AWP (#3)	HW (#4)
Display Reconfig (6.3.2.3)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)
EE Release (6.3.2.4)	HW X 1 (#10)	SW X 1 (#8)	HW X 2 (#9)	SW X 2 (#7)	HW X 1 (#10)	SW X 1 (#8)	HW X 2 (#9)	SW X 2 (#7)	HW X 1 (#10)
Display Reconfig (6.3.2.5)	SW (#11)	SW (#11)	SW (#11)	SW (#11)	SW (#11)	SW (#11)	SW (#11)	SW (#11)	SW (#11)
EE Backoff (Camera Control) (6.3.2.6)	HW (HW) (#14)	SW (SW) (#12)	AWP (AWP) (#13)	HW (Keypad) (#14)	SW (Keypad) (#12)	AWP (SW) (#13)	HW (AWP) (#14)	SW (AWP) (#12)	AWP (HW) (#13)
Camera Controls (6.3.2.2)	SW (#2)	AWP (#3)	Keypad (#5)	SW (#2)	HW (#4)	HW (#4)	Keypad (#5)	Keypad (#5)	AWP (#3)
Display Reconfig (6.3.2.3)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)
EE Release (6.3.2.4)	HW X 2 (#9)	SW X 2 (#7)	HW X 1 (#10)	SW X 1 (#8)	HW X 2 (#9)	SW X 2 (#7)	HW X 1 (#10)	SW X 1 (#8)	HW X 2 (#9)
Display Reconfig (6.3.2.7)	SW (#15)	SW (#15)	SW (#15)	SW (#15)	SW (#15)	SW (#15)	SW (#15)	SW (#15)	SW (#15)
Auto Sequence (Camera Control) (6.3.2.8)	HW (SW) (#17)	SW (AWP) (#16)	HW (Keypad) (#17)	SW (SW) (#16)	HW (HW) (#17)	SW (HW) (#16)	SW (Keypad) (#16)	SW (Keypad) (#16)	HW (AWP) (#17)
Camera Controls (6.3.2.2)	AWP (#3)	Keypad (#5)	SW (#2)	HW (#4)	SW (#2)	AWP (#3)	SW (#2)	HW (#4)	Keypad (#5)
Display Reconfig (6.3.2.3)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)
EE Release (6.3.2.4)	SW X 1 (#8)	HW X 1 (#10)	SW X 2 (#7)	HW X 2 (#9)	SW X 1 (#8)	HW X 1 (#10)	SW X 2 (#7)	HW X 2 (#9)	SW X 1 (#8)
Display Reconfig (6.3.2.5)	SW (#11)	SW (#11)	SW (#11)	SW (#11)	SW (#11)	SW (#11)	SW (#11)	SW (#11)	SW (#11)
EE Backoff (Camera Control) (6.3.2.6)	SW (AWP) (#12)	AWP (Keypad) (#13)	HW (SW) (#14)	SW (HW) (#12)	AWP (SW) (#13)	HW (AWP) (#14)	SW (SW) (#12)	AWP (HW) (#13)	HW (Keypad) (#14)
Camera Controls (6.3.2.2)	Keypad (#5)	HW (#4)	HW (#4)	AWP (#3)	AWP (#3)	Keypad (#5)	HW (#4)	SW (#2)	SW (#2)
Display Reconfig (6.3.2.3)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)
EE Release (6.3.2.4)	SW X 2 (#7)	HW X 2 (#9)	SW X 1 (#8)	HW X 1 (#10)	SW X 2 (#7)	HW X 2 (#9)	SW X 1 (#8)	HW X 1 (#10)	SW X 2 (#7)
Display Reconfig (6.3.2.7)	SW (#15)	SW (#15)	SW (#15)	SW (#15)	SW (#15)	SW (#15)	SW (#15)	SW (#15)	SW (#15)
Auto Sequence (Camera Control) (6.3.2.8)	SW (Keypad) (#16)	HW (HW) (#17)	SW (HW) (#16)	HW (AWP) (#17)	SW (AWP) (#16)	HW (Keypad) (#17)	HW (HW) (#17)	HW (SW) (#17)	SW (SW) (#16)
Display Reconfig (6.3.2.3)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)	SW (#6)
Display Reconfig (6.3.2.5)	SW (#11)	SW (#11)	SW (#11)	SW (#11)	SW (#11)	SW (#11)	SW (#11)	SW (#11)	SW (#11)
EE Backoff (Camera Control) (6.3.2.6)	AWP (Keypad) (#13)	HW (HW) (#14)	SW (HW) (#12)	AWP (AWP) (#13)	HW (AWP) (#14)	SW (Keypad) (#12)	AWP (HW) (#13)	HW (SW) (#14)	SW (SW) (#12)

LEGEND

SW	Baseline Software Implementation
HW	Dedicated Hardware Switch Panel
SW X 1	End Effector Mechanism Malfunction Procedure Using One Software Switch
SW X 2	End Effector Mechanism Malfunction Procedure Using Two Software Switches
HW X 1	End Effector Mechanism Malfunction Procedure Using One Hardware Switch
HW X 2	End Effector Mechanism Malfunction Procedure Using Two Hardware Switches
AWP	Active-While-Pressed Switch Implementation
EE	End Effector
(#)	Checklist Number
(6.3.2.X)	Test Plan Paragraph Description

PAGE C2 [illegible]

PRECEDING PAGE BLANK NOT FILMED

Table C-2: Test Evaluator Summary

Data Set	Name	Date
1	Veach	18 Jan 94
2	Garneau	18 Jan 94
3	Baker	19 Jan 94
4	Clervoy	19 Jan 94
5	Ochoa	21 Jan 94
6	Ford	21 Jan 94
7	Bowersox	24 Jan 94
8	Voss	25 Jan 94
8	Payette (CSA)	26 Jan 94
9	Nicollier	27 Jan 94

PERFORMANCE DATA

Table C-3: Task Completion Times for Various Camera Control Methods (minutes:seconds)

Operator	Camera Control			
	SW	AWP	HW	KP
1	*09:40*	02:55	*05:01*	03:40
2	06:04	04:00	02:19	02:30
3	06:00	03:10	01:55	02:45
4	02:50	02:40	01:50	01:30
5	04:40	02:00	02:00	04:10
6	04:00	03:45	03:00	02:00
7	05:50	02:30	02:00	01:50
8	02:00	02:00	01:45	02:10
9	03:43	04:00	01:30	02:35
10	03:00	02:50	01:30	03:00
Average	04:14	02:59	01:59	02:37
Std Dev.	01:30	00:45	00:28	00:50

Table C-4: Total Overshoots/Undershoots for Various Camera Control Methods

Operator	Camera Control			
	SW	AWP	HW	KP
1	9	9	*10*	8
2	5	5	1	1
3	8	7	4	6
4	3	5	3	2
5	5	4	4	7
6	2	2	0	1
7	7	11	4	3
8	4	0	2	6
9	5	2	1	2
10	4	5	3	3
Average	5.2	5	2.4	3.9
Std Dev.	2.20	3.33	1.51	2.60

Legend for Performance Data Tables:

SW:	Baseline Software	SW1:	One-Button Software	*italics*:	Data point removed by Chauvenet's criterion (see Analysis Techniques, page C-11)
AWP:	Active-While-Pressed	SW2:	Two-Button Software		
HW:	Hardware	HW1:	One-Button Hardware		
KP:	Computer Keypad	HW2:	Two-Button Hardware	N/A:	Data point not available

Table C-5: Erroneous Inputs for Various Camera Control Methods

Operator	Camera Control			
	SW	AWP	HW	KP
1	3	1	0	1
2	1	1	0	0
3	2	0	0	1
4	0	1	0	0
5	0	0	0	1
6	0	0	0	0
7	2	0	*2*	0
8	0	0	0	0
9	1	0	0	1
10	1	*2*	0	1
Average	1.00	0.33	0.00	0.50
Std Dev.	1.05	0.50	0.00	0.53

Table C-6: Task Completion Times for Various Backup Drive Control Methods (minutes:seconds)

Operator	Backup Drive Control		
	SW	AWP	HW
1	04:40	04:00	02:55
2	N/A	07:50	02:45
3	N/A	05:00	*04:45*
4	05:15	05:00	03:15
5	05:30	04:10	03:20
6	04:00	06:00	03:15
7	05:00	04:20	02:40
8	05:32	04:09	04:05
9	04:15	*09:00*	03:02
10	05:15	03:30	03:30
Average	04:56	04:53	03:12
Std Dev.	00:34	01:19	00:26

Legend for Performance Data Tables:

SW:	Baseline Software	SW1:	One-Button Software	*italics*:	Data point removed by Chauvenet's criterion (see Analysis Techniques, page C-11)
AWP:	Active-While-Pressed	SW2:	Two-Button Software		
HW:	Hardware	HW1:	One-Button Hardware		
KP:	Computer Keypad	HW2:	Two-Button Hardware	N/A:	Data point not available

Table C-7: Erroneous Inputs for Various Backup Drive Control Methods

Operator	Backup Drive Control		
	SW	AWP	HW
1	0	0	0
2	N/A	0	0
3	N/A	0	0
4	0	1	0
5	0	0	0
6	0	1	0
7	0	0	0
8	0	0	1
9	*1*	0	0
10	0	0	1
Average	0.00	0.20	0.20
Std Dev.	0.00	0.42	0.42

Table C-8: Task Deviations for Various Backup Drive Control Methods

Operator	Backup Drive Control		
	SW	AWP	HW
1	1	1	1
2	N/A	1	1
3	N/A	2	1
4	0	1	0
5	0	0	0
6	0	0	0
7	0	0	1
8	1	1	0
9	*3*	0	0
10	0	1	0
Average	0.29	0.70	0.40
Std Dev.	0.49	0.67	0.52

Legend for Performance Data Tables:

SW:	Baseline Software	SW1:	One-Button Software	*italics*:	Data point removed by Chauvenet's criterion (see Analysis Techniques, page C-11)
AWP:	Active-While-Pressed	SW2:	Two-Button Software		
HW:	Hardware	HW1:	One-Button Hardware		
KP:	Computer Keypad	HW2:	Two-Button Hardware	N/A:	Data point not available

Table C-9: Task Completion Times for Simultaneous Backup Drive and Camera Operations (minutes:seconds)

Operator	Backup Drive Control											
	SW				AWP				HW			
	Camera Control				Camera Control				Camera Control			
	SW	AWP	HW	KP	SW	AWP	HW	KP	SW	AWP	HW	KP
1		02:45						N/A			*06:00*	
2	03:00						03:30					03:45
3	N/A						05:00			03:00		
4		N/A					04:00		02:45			
5				03:35	08:30					02:45		
6				03:12	09:50					02:55		
7	03:00							06:00			02:55	
8			02:50			05:50						02:55
9			03:20			06:10			03:30			
10		03:20					03:15		03:15			
Average	03:00	03:02	03:05	03:24	09:10	06:00	03:56	06:00	03:10	02:53	02:55	03:20
Totals	Avg.	03:08	Std. Dev.	00:17	Avg.	05:47	Std. Dev.	02:13	Avg.	03:05	Std. Dev.	00:21

Table C-10: Camera Deviations for Simultaneous Backup Drive and Camera Operations

Operator	Camera Control											
	SW			AWP			HW			KP		
	Backup Drive Control			Backup Drive Control			Backup Drive Control			Backup Drive Control		
	SW	AWP	HW	SW	AWP	HW	SW	AWP	HW	SW	AWP	HW
1				1					2		n/a	
2	2							0				0
3	N/A					1		2				
4			0	0				0				
5		0				0				*1*		
6		2				0				0		
7	2								0		0	
8					*2*		1					0
9			0		0		0					
10			2	0				0				
Average	2.00	1.00	0.67	0.33	0.00	0.33	0.50	0.50	1.00	0.00	0.00	0.00
Totals	Average	Std. Dev.		Average	Std. Dev.		Average	Std. Dev.		Average	Std. Dev.	
	1.14	1.07		0.29	0.49		0.63	0.92		0.00	0.00	

Legend for Performance Data Tables:

SW:	Baseline Software	SW1:	One-Button Software	*italics*:	Data point removed by Chauvenet's criterion (see Analysis Techniques, page C-11)
AWP:	Active-While-Pressed	SW2:	Two-Button Software		
HW:	Hardware	HW1:	One-Button Hardware		
KP:	Computer Keypad	HW2:	Two-Button Hardware	N/A:	Data point not available

Table C-11: Final Joint Angles for Simultaneous Backup Drive and Camera Operations (degrees)

Operator	Backup Drive Control											
	SW				AWP				HW			
	Camera Control				Camera Control				Camera Control			
	SW	AWP	HW	KP	SW	AWP	HW	KP	SW	AWP	HW	KP
1		121.3						N/A			119.8	
2	119.8						119.9					119.7
3	N/A						N/A			119.9		
4		119.7					119.8		119.7			
5				119.5	120.7					120.3		
6				121.1	*121.5*					*121.0*		
7	120.3							119.8			119.4	
8			118.7			120.7						119.2
9			120.3			120.1			120.1			
10		119.2					119.7		119.6			
Average	120.1	120.1	119.5	120.3	120.7	120.4	119.8	119.8	119.8	120.1	119.6	119.5
Totals	Avg.	120.0	Std. Dev.	0.85	Avg.	120.1	Std. Dev.	0.43	Avg.	119.7	Std. Dev.	0.34

Table C-12: Task Completion Times for Various LEE Release Control Methods (seconds)

Operator	Control Method			
	SW1	SW2	HW1	HW2
1	10	11	11	11
2	14	9	17	15
3	11	13	18	14
4	10	11	13	11
5	14	N/A	10	12
6	11	9	14	14
7	8	8	9	10
8	12	8	10	14
9	8	11	12	15
10	12	9	11	9
Average	11.0	9.9	12.5	12.5
Std Dev.	2.1	1.7	3.0	2.2

Legend for Performance Data Tables:

SW:	Baseline Software	SW1:	One-Button Software	*italics*:	Data point removed by Chauvenet's criterion (see Analysis Techniques, page C-11)
AWP:	Active-While-Pressed	SW2:	Two-Button Software		
HW:	Hardware	HW1:	One-Button Hardware		
KP:	Computer Keypad	HW2:	Two-Button Hardware	N/A:	Data point not available

Table C-13: Point of Resolution Travel Following Surprise Manual Pause (inches)

Operator	Autosequence Control							
	SW				HW			
	Camera Control				Camera Control			
	SW	AWP	HW	KP	SW	AWP	HW	KP
1		64			24			
2	30					28		
3				50			18	
4				41	21			
5		N/A					25	
6			33					24
7		29					23	
8	50					22		
9			20					22
10				29	*36*			
Average	40.0	46.5	26.5	40.0	22.5	25.0	22.0	23.0
Totals	Avg.	38.4	Std. Dev.	13.9	Avg.	23.0	Std. Dev.	2.8

Legend for Performance Data Tables:

SW:	Baseline Software	SW1:	One-Button Software	*italics*:	Data point removed by Chauvenet's criterion (see Analysis Techniques, page C-11)
AWP:	Active-While-Pressed	SW2:	Two-Button Software		
HW:	Hardware	HW1:	One-Button Hardware		
KP:	Computer Keypad	HW2:	Two-Button Hardware	N/A:	Data point not available

ANALYSIS TECHNIQUES

Initially, the averages and unbiased standard deviations were computed for the data. For time and final joint angle data, the averages were computed for each combination of robot and camera control implementation. In addition, the average and unbiased standard deviations were computed for all of the data points with a common robot control implementation. For the deviation data from the combined robot and camera control task, the averages were computed for each combination of robot and camera control implementation. The average and unbiased standard deviations were then computed for all of the data points within a common camera control implementation.

For some of the data, it appeared that some of the data points could be rejected. Chauvenet's criterion was applied to the data. Chauvenet's criterion consists of computing the average and unbiased standard deviation for the data set. Next, the difference between each data point and the average value is computed. If the ratio of the difference to the standard deviation is greater than a tabulated value for a given data point, that data point can be eliminated. Once all eligible data points have been eliminated, a new average and standard deviation is computed using the remaining data points.[6] By applying Chauvenet's criterion to all of the data sets, several data points were eliminated. Data points which were eliminated are shown in underlined italics.

The outside count test was then applied to pairs of data sets within a common task. The outside count test provides an indication of differences between two data sets. The outside count test consists of counting the number of values in one data set which are larger than all of the values in the other data set. Then, the number of values in the other data set which are smaller than all of the values in the first data set is counted. The overlap test requires that neither count be zero, i.e., one data set cannot have both the largest and smallest value. If the sum of the two counts is equal to or greater than 7, then differences exist between the two data sets. In addition, two inequalities based on the number of values in each data set must be satisfied.[7]

Finally, the rank test was applied to those pairs of data sets which yielded a zero count or a total count of 6 in the outside count test. The rank test provides an indication of differences between multiple data sets. The rank test consists of ranking all of the values for each of the data sets and computing a number based on the ranking. The computed number is then compared to a tabulated value. If the computed number is greater than the tabulated value, then differences exist between the data sets.[8] As a final recheck of the data and results, the rank test was applied to all of the combinations of pairs of data sets.

In summary, the following tables show the results of applying Chauvenet's criterion, the outside count and rank tests to the data.

---

[6] J.P. Holman and W.J. Gajda, Experimental Methods for Engineers, 4th ed. (New York: McGraw-Hill Book Company, 1984), pp. 72-73.
[7] E.A. Avallone and Theodore Baumeister, Mark's Standard Handbook for Mechanical Engineers, 9th ed. (New York: McGraw-Hill Book Company, 1987), pp. 17-23 to 17-24.
[8] Ibid, pp. 17-24 to 17-25.

Table C-14: Differences in Task Completion Times for Various Camera Control Methods

SW/AWP	SW/HW	SW/KP	AWP/HW	AWP/KP	HW/KP
No Difference	Different	Different	Different	No Difference	No Difference

Table C-15: Differences in Total Overshoots/Undershoots for Various Camera Control Methods

SW/AWP	SW/HW	SW/KP	AWP/HW	AWP/KP	HW/KP
No Difference	Different	No Difference	No Difference[9]	No Difference	No Difference

Table C-16: Differences in Erroneous Inputs for Various Camera Control Methods

SW/AWP	SW/HW	SW/KP	AWP/HW	AWP/KP	HW/KP
No Difference	Different	No Difference	No Difference	No Difference	No Difference

Table C-17: Differences in Task Completion Times for Various Backup Drive Control Methods

SW/AWP	SW/HW	AWP/HW
No Difference	Different	Different

Table C-18: Differences in Erroneous Inputs for Various Backup Drive Control Methods

SW/AWP	SW/HW	AWP/HW
No Difference	No Difference	No Difference

Legend for Data Analysis Tables:

SW:	Baseline Software	SW1:	One-Button Software
AWP:	Active-While-Pressed	SW2:	Two-Button Software
HW:	Hardware	HW1:	One-Button Hardware
KP:	Computer Keypad	HW2:	Two-Button Hardware

[9] Using the most equitable distribution of ranks between the AWP and HW data, the computed number for the rank test is 3.84. In order to say that the two data sets are different, the computed value must be greater than 3.841. Because there are several values which are common to both data sets, the computed number will be larger or smaller than 3.841, based on how the ranks are distributed. However, the average computed number for all possible combinations of rank distributions is 3.854, which is greater than 3.841. A more sophisticated test may reveal a difference between the AWP and HW data sets.

Table C-19: Differences in Task Deviations for Various Backup Drive Control Methods

SW/AWP	SW/HW	AWP/HW
No Difference	No Difference	No Difference

Table C-20: Differences in Task Completion Times for Simultaneous Backup Drive and Camera Operations

SW/AWP	SW/HW	AWP/HW
Different	No Difference	Different

Table C-21: Differences in Camera Deviations for Simultaneous Backup Drive and Camera Operations

SW/AWP	SW/HW	SW/KP	AWP/HW	AWP/KP	HW/KP
No Difference	No Difference	No Difference	No Difference	No Difference	No Difference

Table C-22: Differences in Final Joint Angles for Simultaneous Backup Drive and Camera Operations

SW/AWP	SW/HW	AWP/HW
No Difference	No Difference	No Difference

Table C-23: Differences in Task Completion Times for Various LEE Release Control Methods

SW1/SW2	SW1/HW1	SW1/HW2	SW2/HW1	SW2/HW2	HW1/HW2
No Difference	No Difference	No Difference	Different[10]	Different	No Difference

Table C-24: Differences in Point of Resolution Travel Following Surprise Manual Pause

SW/HW
Different

Legend for Data Analysis Tables:

SW:	Baseline Software	SW1:	One-Button Software
AWP:	Active-While-Pressed	SW2:	Two-Button Software
HW:	Hardware	HW1:	One-Button Hardware
KP:	Computer Keypad	HW2:	Two-Button Hardware

[10] Using the most equitable distribution of ranks between SW2 and HW1 data, the computed number is 4.167. However, depending on how the ranks are distributed, the results can be interpreted that the data sets are similar or different.

APPENDIX D

CREW CONSENSUS REPORT

WORKSTATION EVALUATION CREW CONSENSUS REPORT

The primary purpose of this test was to evaluate Workstation controls. The results of this test will help complete development of the functional requirements for off-screen (i.e., hard switch) controls for the Workstation to support robotic and camera control tasks. Three sets of controls were evaluated using both on-screen and off-screen implementations. These included:

- Camera Controls
- SSRMS Back-up Drive Controls (Forward, Reverse and Stop; Joint Select; Latching End Effector (LEE) Release; LEE Open Snares; and LEE Retract Latches)
- Autosequence Controls (Resume, Pause, and Stop)

The specific objectives of the test were to:

- Determine which control implementations could be used by the crew to safely and effectively execute the tasks.
- Determine any differences in the crew's ability to execute the tasks using the various control implementations.
- Determine which control implementations the crew preferred to use in executing the tasks.

Crew evaluations had previously been conducted by the Displays and Controls (D&C) Mode Team to define the display (i.e., on-screen data and command) requirements to support Robotic operations. These studies concluded that some hard switch controls were required to support robotics (emergency stop and brakes on/off switches). They also concluded that some camera operations on the Workstation could not be adequately accomplished using software switches (pan, tilt, and zoom).

This test continued the assessment of the robotic and camera controls. It was requested by the Canadian Space Agency (CSA) to close out outstanding review item discrepancies from the Work Package 2 Critical Design Review in support of Workstation development. A total of ten 3-hour evaluations by nine NASA crew members and one representative of the Canadian Astronaut Program Office were conducted.

The test was conducted in the Space Station Mockup and Trainer Facility (SSMTF). The SSMTF is located in Building 9NW of the Johnson Space Center and is part of the Mockup and Integration Laboratory (MAIL). The SSMTF consists of full scale mockups of the habitable portions of the International Space Station configuration and selected part task trainers and systems. The Node Mockup and Workstation was used for this test.

The Node Workstation had three 1024 X 768 pixel, 14 inch diagonal monitors which gave a true 14 inch diagonal active image. The monitors and video hardware and software supported X-windows operations on the three displays with mouse tracking across all displays. The Workstation used UNIX running on an Intel 486 computer processing unit. RGB Spectrum boxes were used to give NTSC overlays on all three monitors.

All hard switches and hand controllers were connected to Allen-Bradley Programmable Logic Controllers. These controllers performed signal processing and logic operations, and read and write operations to the SSMTF shared database.

Previous testing had determined the requirement for some off-screen controls. These controls were provided in this study so that a high fidelity human-computer interface was provided for the crew evaluation. These controls included the Emergency Stop Switch and the Brakes on/off switch.

The basic screen, camera control, and camera stringing displays were developed by the Space Station Reconfiguration Office (DP4). The SSRMS displays were developed by CSA/SPAR and implemented by ER3. All displays were built from the SAMMI version 2.1 format editor and run in the SAMMI V 2.1 runtime environment.

The simulated cameras had pan, tilt, and zoom control and the facility camera had pan, tilt, zoom, focus, and iris control. Camera control was available through the keyboard keys, hard toggle switches, and computer on-screen controls.

Each operator was given a briefing before the start of the test session. Emphasis was placed on test objectives, evaluation criteria, and familiarization with the tasks and displays/controls. The Workstation layout/ergonomics and the display formats/configurations were not evaluated. This was stressed during the pretest briefings. General comments about the Workstation were not solicited directly during the test but all comments made by the test operators were recorded and documented to help with completion of display and control implementation. Each operator had an opportunity to record general Workstation comments in a post-test questionnaire.

An attempt was made to minimize the effect of latency on the test results (i.e. the latencies were reduced to the minimum practical level and were set to be approximately equal for each switch implementation). These latencies were not evaluated.

Switch configurations were evaluated in a different order by each test operator to avoid bias. Switch combinations for simultaneous robotic and camera operations were different for each operator to isolate problems with specific combinations.

The following includes a task description and the crew's final conclusions and recommendations on the tasks and switch implementations evaluated during the Workstation test:

Camera Control Operation

A camera located in the building 9 high bay was used for testing the camera controls. This camera was mounted above the tourist walkway and gave a plan view of the mockups. It was controllable from the Workstation and was selected because of its pan, tilt, focus, iris, and zoom control capabilities. This camera was not a flight-representative camera, but it was assumed to be representative for the purposes of evaluating the different switch implementations.

Four types of camera controls were evaluated; these included the on-screen baseline controls, on-screen active-while-pressed (AWP) controls, off-screen controls on a camera control panel, and off-screen controls on a keypad.

The operator selected a "real" camera view using the high bay camera. The camera was initially positioned full right, level, fully zoomed out, focused for the far zoom setting, and iris fully closed. The test procedure required the operator to open the iris, pan/tilt to find a sign on the high bay floor, zoom in on the sign, and then adjust the iris and focus to permit reading the sign. Following each iteration, the operator rated the specific switch implementation for the capability and ease of performing the camera control task.

Camera control using off-screen hardware controls on a camera control panel was the preferred implementation; however, the keypad was an acceptable option. If the keypad controls are not selected as the primary camera control system, they could be ideally implemented as a redundant or backup system if the implementation is not too difficult or costly. The crew was able to most accurately control the camera using the hardware switches, followed by the off-screen keypad controls, the AWP controls and the baseline software controls. They also felt that the hardware switches would provide for positive habit transfer from the orbiter camera controls, thereby reducing training time. Every hardware switch would ideally have a software backup. Grouping of camera controls in one location was also viewed as important. Although there were no direct safety implications with any of the camera controls, it was felt that the "latch on" feature of the baseline software might have an indirect safety impact during time-critical tasks (because it was slow and cumbersome). The baseline software implementation was clearly inefficient and potentially risky.

Tip End Effector Release

This test scenario required the operator to monitor the end effector for malfunctions and release the end effector if a malfunction was detected. The task was initialized with the SSRMS connected to a grapple fixture. A caution and warning event for an End Effector Mechanism Malfunction was activated by the test conductor. The operator responded with either (1) a **LEE Release** or (2) a **LEE Retract Latch** followed by **LEE Open Snare**, depending on the switch implementation being tested. Following each iteration, the operator rated the appropriate switch implementation.

The task was accomplished four times using (1) on-screen (one switch), (2) on-screen (two switch), (3) off-screen (one switch), and (4) off-screen (two switch) procedure controls.

One hardware switch which accomplishes both the latch retraction and snare release should be implemented. However, it should be guarded to prevent inadvertent operation. Feedback should be provided to the operator to indicate when the LEE has been released by using a lighted switch. A screen display for feedback, similar to the system which was evaluated (command sent/executed), is desirable. It is also desirable that an on-screen, two button LEE release configuration be provided as a backup. If implemented, it should consist of an **ARM** button and a **LEE RELEASE** button to prevent accidental activation, which is possible with a single button software configuration. The one switch, on-screen implementation which was tested was considered unsafe due to the possibility of accidental activation during on-orbit operations.

Back End Effector Away From Grapple Pin

During this task, the operator backed the SSRMS off a grapple fixture using backup drive controls. The primary view used was the tip end effector camera view which included an overlay box. The test operator attempted to keep the grapple pin within the confines of the box while performing the task. Following successful back-off of the end effector, the operator repositioned the SSRMS to a specific elbow pitch angle. During this reposition, the operator was asked to keep the end effector in the center of one of the camera views (simultaneous robotic and camera operations). The camera control was varied between operators using several different implementations. Following each iteration, the operator rated the specific switch implementation.

Three switch implementations were used to accomplish the tasks. They were on-screen baseline, on-screen active-while-pressed, and off-screen controls on a dedicated hardware panel.

The preferred implementation for the SSRMS backup drive controls was off-screen controls on a dedicated hardware panel. However, a modified version of the active-while-pressed configuration would also be acceptable as the implementation. This modification should allow for movement of a specific joint in a specified direction with the actuation of one button. With this modification, the crew would prefer which ever implementation is most cost effective. The baseline software which permitted "latch-on" movement of the SSRMS is unsafe and should not be considered.

Autosequence

The purpose of this task was to monitor and control an autosequence. The SSRMS was initialized at the autosequence starting point. Three separate autosequence movements were made. During the first, the operator monitored the movement of the SSRMS. During the second, the operator initiated the autosequence, manually paused at a prebriefed arm position, and then restarted the autosequence. During the third autosequence, the test conductor asked the operator to manually pause the autosequence. This requirement was not known to the operator prior to this point. The operator then restarted the sequence and completed the task. During the autosequence task, the operator tracked the SSRMS using two camera views (simultaneous robotic and camera operations). The camera control was varied between operators using several different implementations. Following completion of all three movements, the operator rated the specific switch implementations for the capability and ease of doing the tasks.

Two switch implementations were evaluated. They were on-screen baseline and off-screen controls on a dedicated hardware panel.

The preferred autosequence controls for the SSRMS are off-screen controls on a dedicated hardware panel. Although not preferred, the baseline software controls were acceptable.

The following are general test observations and comments:

1. The layout of the displays requires major modification:

   A. The operational paths of each on-screen function need to be defined and shortened. There was too much distance between buttons, requiring excessive cursor movement and increased operation time.

   B. There needs to be sufficient talkback (continuous and easily recognizable) for all selected on-screen functions to provide constant feedback to the operator as to what switches are engaged.

   C. The active area for switch actuation needs to be enlarged (perhaps "snap-to" software would help also).

   D. All references to joint direction of movement need to be "+" and "-" rather than **FORWARD** and **REVERSE**.

2. For functions which require a set amount of time to complete (i.e. LEE release), a counter, displaying the time from switch actuation, would be helpful. This could be in the form of a pop-up display.

3. The trackball was too sensitive.

4. The keyboard and trackball should be transportable so that the operator can move away from the workstation with one or the other, or both, if desired.

5. A trackball which can be gripped and which can be attached to either the right or left side of the keyboard is desirable.

6. Due to the number of tasks that the robotics operator will be faced with (camera control, lighting, robotics, and systems monitoring), alternative camera control techniques should be explored, i.e., voice actuation, foot actuation, or integration on the RHC or THC.

7. The order of the monitors was unsatisfactory. The numbering needs to be changed so that it runs left to right and top to bottom.

8. Audio alert is necessary for malfunction occurrence.

9. The auto sequence status line should be color-coded to make status changes more recognizable.

10. The brake switch on the hard panel should have talkback capability (in addition to the on-screen indication).

11. The capability should exist to change speeds (coarse/vernier) during movement of the camera and SSRMS.

12. "Latch on" motion commands are potentially hazardous and should not be provided as the primary control method except for the autosequence function. In all other cases, the "dead man switch" implementation should be used on-orbit due to the relative likelihood of operator distraction in a multi-task environment. A rate hold feature is a useful adjunct for certain types of operations and should be provided as an operator-selectable option.

13. This test assessed controls in terms of safety, efficiency, and crew preference. For cases where on-screen controls might be as safe and efficient as off-screen controls, other factors, such as weight, volume, cost, testing requirements, ease of maintenance, and impact of redesign should be considered in the final selection.

14. Operators should not have to focus completely on sensor (camera) controls while performing a robotic task. The main concern of the operator is the robotic task itself. Sensors should be selectable/ controllable without requiring long periods of dedicated attention.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May/94	Technical Memorandum

4. TITLE AND SUBTITLE
International Space Station Alpha Remote Manipulator System Workstation Controls Test Report

5. FUNDING NUMBERS

6. AUTHOR(S)
William A. Ehrenstrom, *Colin Swaney, Patrick Forrester

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Station-Exploration Support Office
Lyndon B. Johnson Space Center
Houston, Texas 77058

8. PERFORMING ORGANIZATION REPORT NUMBERS
S-770

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, D.C. 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
TM-104796
JSC-26704

11. SUPPLEMENTARY NOTES

*Rockwell Space Operations Company, Houston, Texas

12a. DISTRIBUTION/AVAILABILITY STATEMENT
unclassified/unlimited
Available from the NASA Center for AeroSpace Information
800 Elkridge Landing Road
Linthicum Heights, MD 21090
(301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
Previous development testing for the Space Station Remote Manipulator System Workstation controls determined the need for hardware controls for the emergency stop, brakes on/off, and some camera functions. This report documents the results of an evaluation to further determine control implementation requirements, requested by the Canadian Space Agency (CSA) to close outstanding review item discrepancies. This test was conducted at the Johnson Space Center's Space Station Mockup and Trainer Facility in Houston, Texas, with nine NASA astronauts and one CSA astronaut as operators. This test evaluated camera iris and focus, back-up drive, latching end effector release, and autosequence controls, using several types of hardware and software implementations. Recommendations resulting from the testing included providing guarded hardware buttons to prevent accidental actuation; providing autosequence controls and back-up drive controls on a dedicated hardware control panel; and that "latch on/latch off", or on-screen software, controls not be considered. Generally, the operators preferred hardware controls although other control implementations were acceptable. The results of this evaluation will be used along with further testing to define specific requirements for the Workstation design.

14. SUBJECT TERMS
space stations, workstations, human factors engineering, man machine systems, productivity, remote manipulator system, control systems, control boards

15. NUMBER OF PAGES
80

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclassified	unclassified	unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std. 239-18
298-102