Proceeding of the 6th International Symposium on Artificial Intelligence and Robotics & Automation in Space: i-SAIRAS 2001, Canadian Space Agency, St-Hubert, Quebec, Canada, June 18-22, 2001.

JEMRMS Design Features and Topics from Testing

Naoki Sato, Yasufumi Wakabayashi

JEM Project Team, National Space Development Agency of Japan
2-1-1, Sengen, Tsukuba-shi, Ibaraki, 305-8505, JAPAN
E-mail: satoh.naoki@nasda.go.jp

Keywords JEMRMS, Space Station, Operability, Testing

Abstract

The JEMRMS consists of three major subsystems, the Console, Main Arm (MA), and Small Fine Arm (SFA). Each subsystem has already bean manufactured and has been subjected to many kinds of tests. This paper outlines each subsystem and system, and reports several topics from the testing.

The Console has been subjected to environmental tests, a thermal balance test and a modal survey for the mathematical model correlation, integrated software test, and maintainability test. No major anomaly was found in the environmental tests but an EMC issue was discovered. Also, acoustic noise violated the requirement, but this will be fixed. Furthermore, several minor bugs were found and fixed during the integrated software test.

The MA has also been subjected to environmental tests, a modal survey, and a thermal balance test for the mathematical model correlation. The performance test was then conducted on the flat floor test bed. In this test, basic robotics performance data, such as step input response, emergency stop distance, and positioning accuracy were acquired. All results satisfied the specifications. The acquired data were incorporated into the detailed simulation model. Using this model, we verified the actual on-orbit performance.

We connected the Console and the MA, and performed Human In the Loop (HIL) test #1 as an operability test using five robotics-certified astronauts. During this test, we observed continued motion of the MA. The MA control algorithm will be therefore changed.

The SFA has also passed a series of environmental and performance tests. Some problems concerning the harness routing occurred but were fixed. Life verification of the gears was also challenging.

As a final step of the JEMRMS system testing, we will conduct performance tests on the flat floor connecting all three subsystems in May 2001. Also, we will demonstrate the operability of the SFA at HIL #2.

1. JEMRMS System Overview

1.1 Console

The console is a robotics workstation. It is composed of the Management Data Processor (MDP), Arm Control Unit (ACU), two TV monitors (TVMs), a Translational Hand Controller (THC), a Rotational Hand controller (RHC), an RMS Lap Top Computer (RLT), and other components. The MDP is the main computer that controls the JEMRMS mode and collects telemetry. The ACU receives the hand controllers' signal, calculates the arm trajectory and inverse kinematics, and sends angle commands to joints. The RLT displays telemetry such as the arm position, joint angles, micro-switch status, and other telemetry on the graphical user interface (GUI). Figure 1 shows the Console overview.

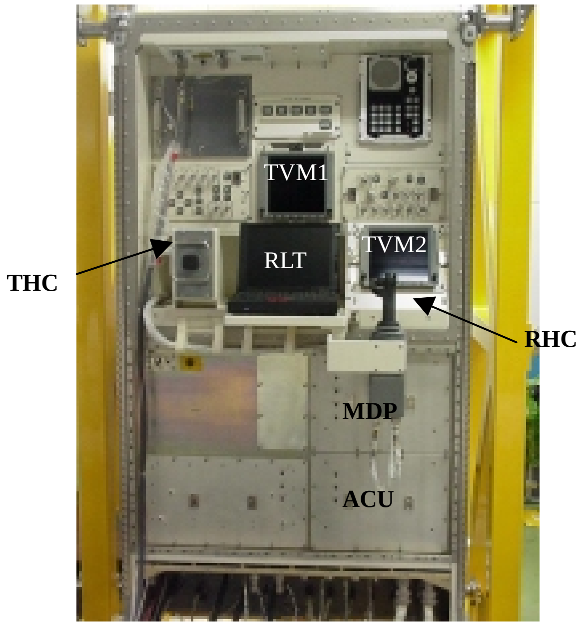

Figure 1: Console Overview

1.2 Main Arm

The Main Arm (MA) is a 10m, six-degree-of-freedom robot arm. It consists of three booms, six joints, an end effector on the tip, and two vision systems (one on the shoulder, the other on the tip). The two main booms are made of Carbon Fiber Reinforced Plastic (CFRP) to minimize thermal effects on orbit. DC servomotors with planetary gears drive joints. A resolver and an optical encoder are installed on each joint. The End effector can grapple the space station common grapple fixtures. Figure 2 shows the MA overview.

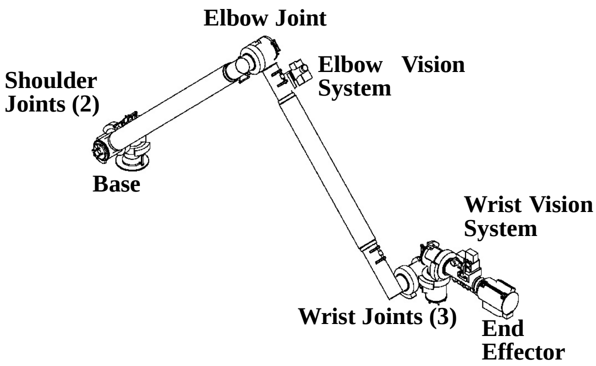

Figure 2: MA Overview

1.3 Small Fine Arm

The Small Fine Arm (SFA) is also a six-degree-of-freedom robot arm. It can perform more dexterous tasks than the MA. During operation, the SFA is grappled by the MA and receives power and data from the MA. The 2m SFA consists of two booms, six joints, and an end effector on the tip called the “tool,” and a camera on the tool. The tool has a force and torque sensor inside it for compliance operation. A DC servomotor drives joints with a harmonic drive.

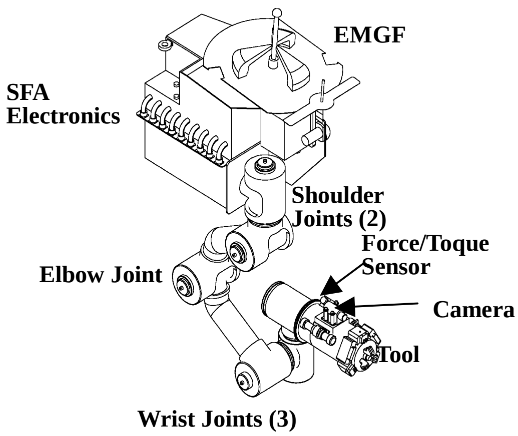

Figure 3: SFA Overview

1.4 JEMRMS System Performance

Table 1 shows the major system performance characteristics of the JEMRMS. These are verified by test and analysis. Positioning accuracy is relative to the base coordinate system of each arm.

Table 1: JEMRMS Major System Performance

Main Arm	
Positioning Accuracy	+/-50mm, +/-1.0deg
Maxi. PL Handling Weight	7000kg
Maximum Speed	60mm/sec, 2.5deg/sec
Emergency Stop Distance	300mm, 5.0deg
Small Fine Arm	
Positioning Accuracy	+/-10mm, +/-1.0deg
Maxi. PL Handling Weight	300kg
Maximum Speed	50mm/sec, 7.5deg/sec
Emergency Stop Distance	50mm, 5.0deg
Ranging (Relative position measurement between wrist camera and target)	
Accuracy	+/-12.0mm, +/-1.22deg

Ranging is a unique function of the JEMRMS that determines the arm tip position and attitude relative to the target. Figure 4 shows the geometry of the arm and the dedicated target. A crewmember will see the target image on the TV monitor through the tilted wrist camera (see Figure 5). A crewmember pinpoints the white dot on the TV monitor using the cross hair cursor. By comparing the ideal white dot location and designated position, the crewmember can determine the MA relative position and attitude to the target by MDP software. This performance is going to be verified in a series of the proto-flight system testing. Safety function is described in reference [1].

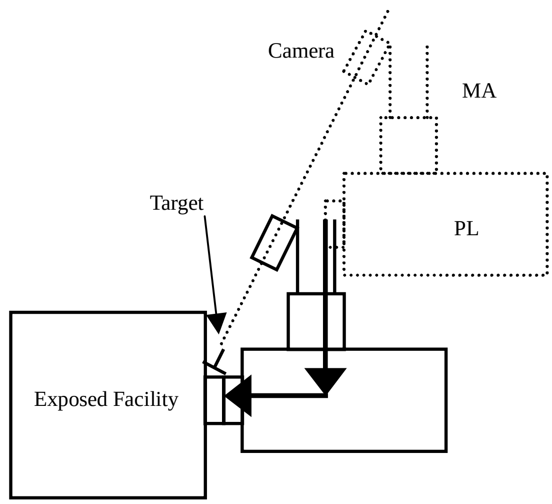

Figure 4: Ranging Configuration

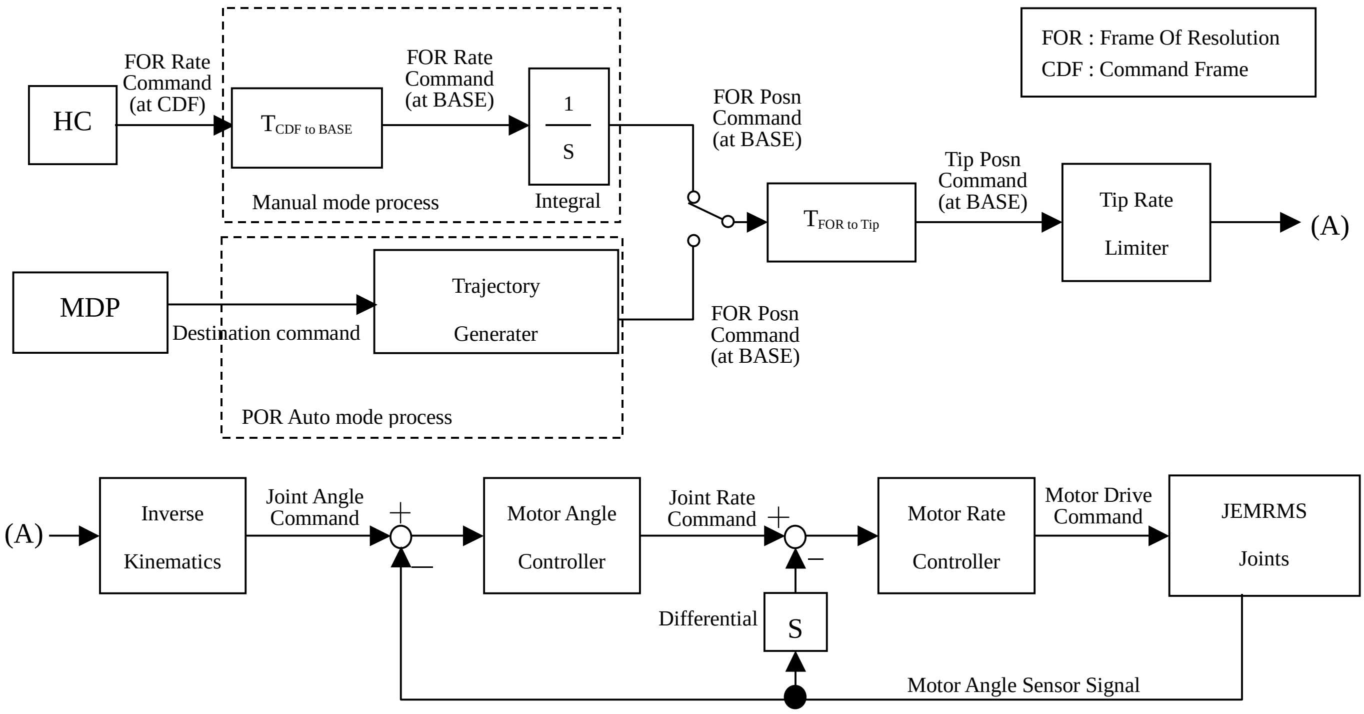

Figure 6: JEMRMS Control Schematics

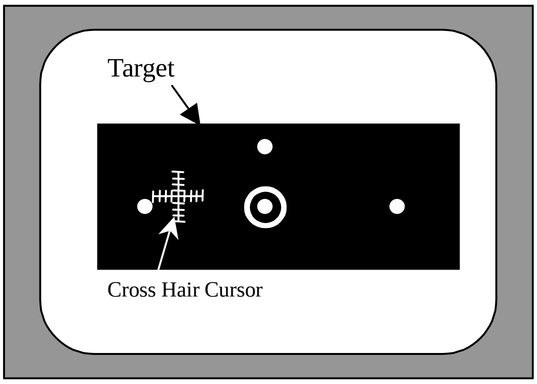

Figure 5: Target on the TV Monitor

1.5 JEMRMS Control Schematics

Figure 6 shows the simplified JEMRMS control schematics. The control converts the rate command from the Hand-Controller to a position command. In case of SFA control, a motor rate controller, including a current controller, is installed in the SFA electronics unit. More detail discussion can be found in references [2] and [3].

2. Subsystem Testing
2.1 Console Testing

The console proto-flight model has been subjected to two environmental tests, the vibro-acoustic test and EMC test. Structural integrity tests (random vibration test and static load test) were performed on the dedicated structural qualification model. Other environmental tests (thermal vacuum test and humidity test) were conducted at the component level. Also, a modal survey and a thermal balance test were conducted on the proto-flight model to correlate the mathematical models. The maintainability test was performed with astronaut participation to evaluate the accessibility, visibility, and tool fit. All maintenance tasks were evaluated and were accepted. The integrated S/W test was another major subsystem test. The integrated S/W test verifies the interface integrity of the S/W among the components. Typical commands and feedback through JEMRMS system components were verified. Also, responses of the S/W to the anomaly situations such as angle telemetry errors and communications errors simulated by the arm simulator were tested for safety verification.

The Space Station program has a stringent acoustic noise requirement of NC-50 for each laboratory module from crew safety standpoints. The acoustic noise radiation level was measured but exceeded the console noise level of NC-40 between 500 and 1kHz (see Figure 7). The major noise source was found to be the avionics air fan. Decreasing the fan speed in the scope while maintaining the air-cooling capability will reduce the noise radiation.

In the EMC test, the RHC exhibited susceptibility to the high radiation noise of 60V/m at 250-270MHz. Error output of the RHC exceeding the dead band was counted (see Figure 8). A similar anomaly was also found in the EMC test of the SSRMS Robotics Workstation. The Hand Controller is common Space Station hardware. The cause of this anomaly is expected to be the radiation of noise through the rubber boot of the joystick (see Figure 9). Installing a conductive boot on the joystick or eliminating the clearance between the boot and base plate will fix the problem.

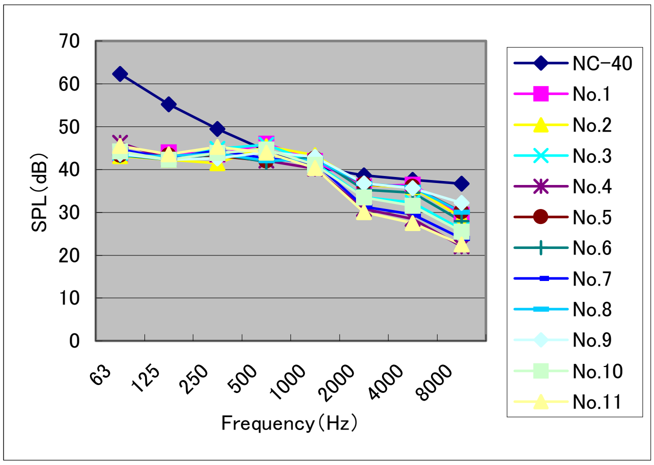

Figure 7: Console Acoustic Noise Level

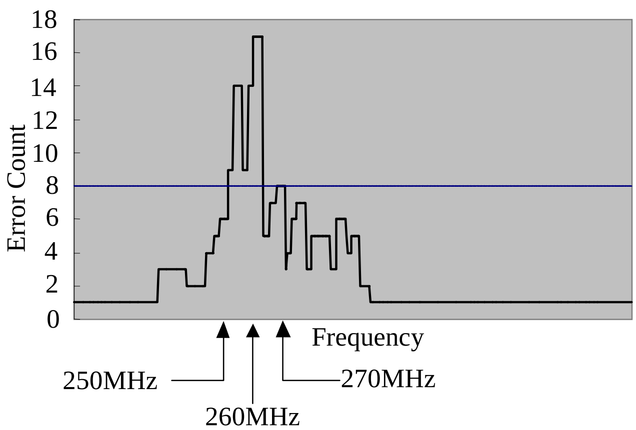

Figure 8: RHC Error Due to EMC Noise

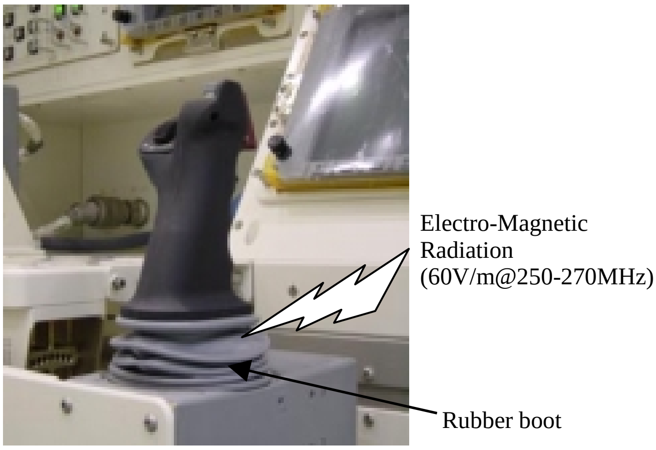

Figure 9: RHC Radiation Susceptibility

2.2 Main Arm Testing

Only an EMC test was conducted on the Main Arm (MA) proto-flight model as an environmental test. A static load test was performed on the MA structural qualification model. Structural integrity for random vibration was verified by performing the vibro-acoustic test on the JEM Pressurized Module (see Figure 10). Thermal vacuum tests were conducted at the component level. Also, a modal survey and thermal balance test were conducted on the MA proto-flight model to correlate the mathematical models of the MA.

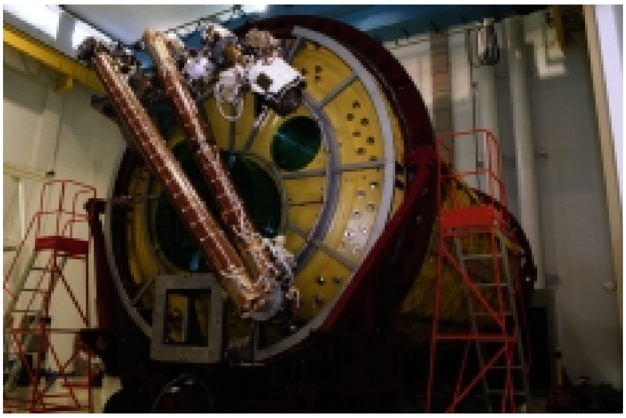

Figure 10: Main Arm Installed on the Pressurized Module

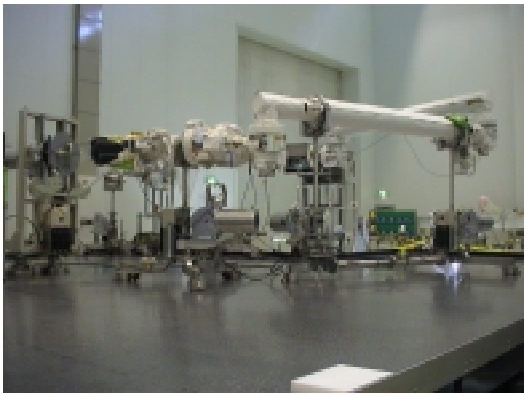

Figure 11: Main Arm Test on the Air Bearing Test Bed

The MA control characteristics, i.e. step input response of each joint, positioning accuracy, corridor error, and emergency stop distance, were tested on the air bearing test bed (see Figure 11). The friction factor of this air bearing test bed is less than 0.003. Figures 12 to 14 show the test results of the response of the shoulder, elbow, and wrist pitch joint to a step input of 1.0 deg (no payload at the end effector). The thick line is the output axis response, the thin line is the motor axis response, and the dotted line is the command input.

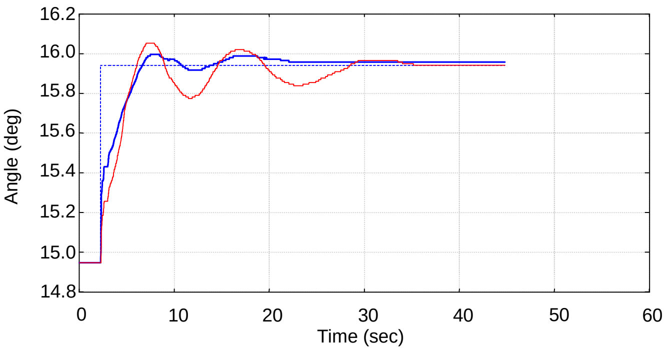

Figure 12: Shoulder Pitch Step Input Response (Test)

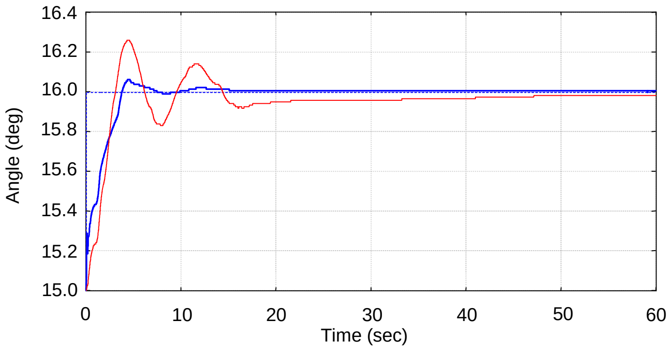

Figure 15: Shoulder Pitch Step Input Response (Analysis)

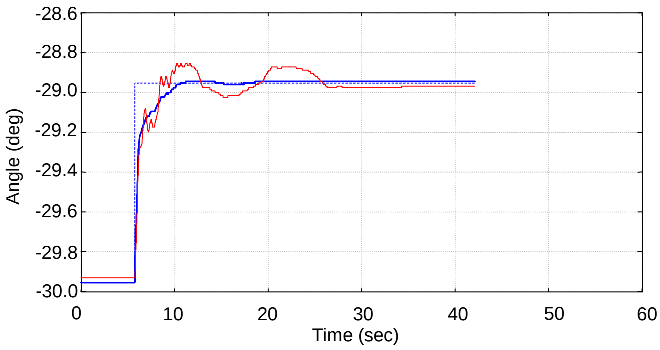

Figure 13: Elbow Pitch Step Input Response (Test)

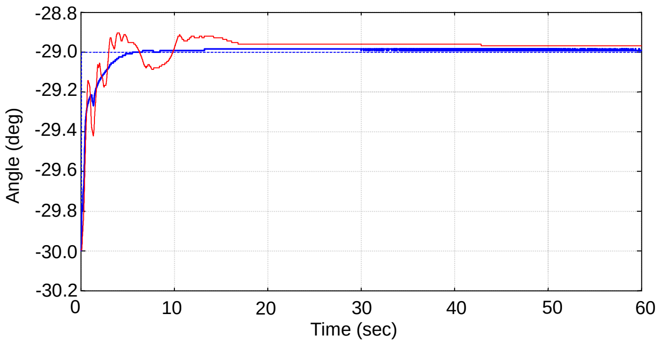

Figure 16: Elbow Pitch Step Input Response (Analysis)

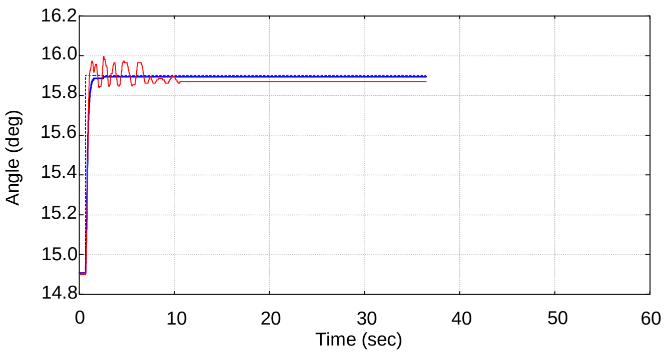

Figure 14: Wrist Pitch Step Input Response (Test)

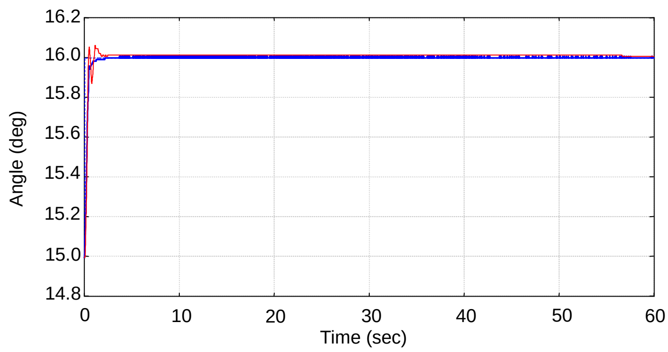

Figure 17: Wrist Pitch Step Input Response (Analysis)

Figures 15 to 17 show the results of the post-test analysis. The responses of the motor axis of the test and analysis are very similar, except that the stabilizing time during the test is a little bit longer than the analysis due to friction. The qualitative output axis responses of the test and analysis are also similar. However, the rise time, overshoot, and residual deviation are different due to friction and depend on the initial condition difference between test and analysis. That is, the gear is initially positioned at the center of the backlash in the analysis, but it’s not so limited in the actual test. Table 2 summarizes the comparison between the test and analysis. Because the analyzed motor angle response corresponds well to the test results, we concluded that the MA dynamic model was properly correlated.

Using the correlated arm dynamic model, we analyzed and assessed the on-orbit performance. Tables 3 and 4 show the analysis results of the on-orbit positioning error and emergency stop distance. The results satisfy the allocation derived from the system performance requirements.

Table 2: Comparison Between Test and Analysis (Shoulder Pitch Joint Case)

Item	Test	Analysis
Motor axis rise time（sec）	3.424	3.376
Output axis rise time（sec）	3.176	2.408
Motor axis delay time（sec）	0.792	1.296
Output axis delay time（sec）	1.616	1.680
Motor axis overshoot（deg）	0.056	0.063
Output axis overshoot（deg）	0.112	0.262
Motor axis settling time（sec）	18.968	15.056
Output axis steady state error（deg）	0.103	0.080

Table 3: On-orbit Positioning Performance

Case		Translation Error (mm)			Attitude Error (deg)		
		dX	dY	dZ	Roll	Pitch	Yaw
1	Motor Axis	1.1	0.0	1.5	0.000	0.025	0.000
	Output Axis	3.1	0.9	7.6	0.000	0.086	0.001
2	Motor Axis	1.5	0.0	0.1	0.0	0.001	0.0
	Output Axis	2.5	0.3	5.6	0.002	0.110	0.004
Allocation		26.8 or less			0.25 or less		

Case 1: Z-direction operation
Case 2: X-direction operation

Table 4: On-orbit Emergency Stop Distance

Grappled PL mass/Speed	Translation (mm)	Rotation (deg)
0.6 ton@60mm/sec	129.6	0.77
3.0 ton@30mm/sec	121.6	0.87
7.0 ton@20mm/sec	118.7	0.88
Allocation	256.2 or less	1.69 or less

2.3 Small Fine Arm Testing

The SFA was also subjected to a series of environmental tests and the thermal balance test. Because the SFA itself has a joint rate controller only, the major robotics performance test consisted of only joint rate controllability. Positioning accuracy, emergency stop distance and compliance control will be tested in the end-to-end system test. The most difficult issue in the SFA system test was the harness routing and interface. As can be seen in Figure 18, the harness to the joints and tool is routed outside of the boom or joints because the harness drum application could violate the SFA stowed envelope. However the SFA has a large reach capability, so the harness needs to be long enough to maintain the reach capability. Several protrusions have been found during the dimension check, but they were all fixed by adding an additional guide and/or clamp.

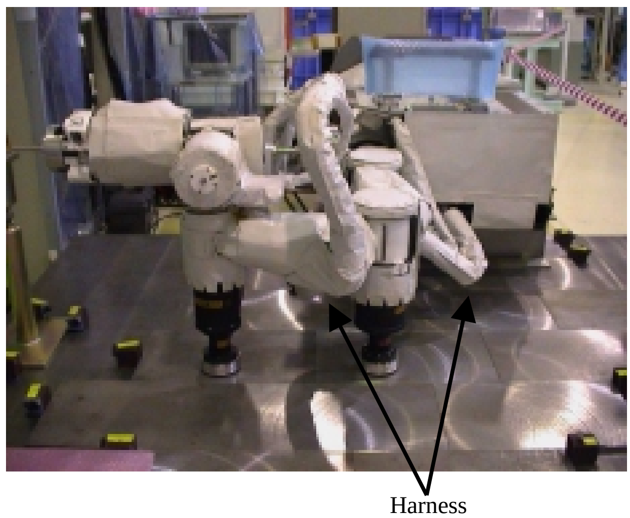

Figure 18: SFA Flat Floor Testing

2.4 Human In the Loop Test #1

Five astronauts using the proto-flight model of the MA and Console as well as simulators conducted Human In the Loop (HIL) Test #1. Astronauts assessed the arm dynamics, situational awareness and Graphical User Interface (GUI). Several minor GUI modifications were recommended and implemented. Additionally, one concern on the arm control dynamics was noted. More detail is described in reference [4].

(1) Phenomena
During RHC operation, the MA continued to move even after the crewmember released the RHC. Data log analysis showed that the crewmember tilted the RHC suddenly to the maximum position around the Y-axis (Pitch down) with the command frame being on the base and kept it for 22 seconds. The MA then continued to move in the Z-direction for about 90 seconds even after the RHC was released.
(2) Cause
The cause was as follows. The tip rate command from the RHC is converted to the “FOR position command at the BASE coordinate system.” After the tip rate limiter is passed, the tip position command is converted to a joint-angle command and sent to each joint. At each joint, the angle command is converted to a joint-rate command and a motor-drive command in sequence (refer to Figure 6). The tip rate command from the HC is not converted to an angle-rate command directly but converted to the FOR position command at the BASE coordinate system in order to sustain the command frame direction even if the MA is disturbed on orbit by other space station elements. For example, for a command frame on the tip, the command frame is easily changed by disturbances. The MA would thus move in an unexpected direction if the rate command from the HC were directly converted to an angle-rate command. During the test, the MA is almost fully deployed to a length of 7.44 m (see Figure 19). The total accumulated translation command was therefore 7.44m*sin (2.5(deg/sec)*22(sec))=6.09m. However, the tip translation rate is limited to 0.06m/sec, so the MA moved only 0.06m/sec*22sec=1.32m while the RHC is tilted. Therefore, a positioning command of 4.77m=6.09m-1.32m was still unexecuted and was observed as continued motion after the RHC was released.
(3) Solution
In order to prevent the accumulation of the rate command, a FOR rate limiter will be added before the rate command is converted to the position command.

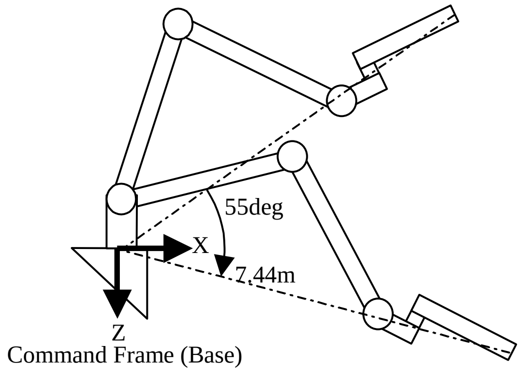

Figure 19: MA Configuration During Continued Motion

3. Future Activity

Some testing, such as the end-to-end system test connecting the SFA, MA, and Console, HIL #2, and ranging performance test, remains and will be conducted around May and June 2001. This concludes all JEMRMS verification tests. A Post Qualification Review (PQR) will follow in August 2001. Also, a JEM overall system integration test will be performed from this October.

4. Conclusion

These tests and following analyses verified that the JEMRMS has enough performance capability on-orbit; several tests remain to be conducted.

5. Acknowledge

The JEMRMS has been developed with support of Toshiba Corporation and Hitachi, Ltd. The authors appreciate their important contributions and hard work in the development.

References

[1] T. Matsueda, T. Satoh, N. Sato, Y. Hisadome, S. Doi, “Safety Approach of Japanese Experiment Module Remote Manipulator System.” ISAIRAS ‘99
[2] H. Morimoto, Y. Kasama, S. Doi, Y. Wakabayashi, “Motion Control of the Small Fine Arm for the Japanese Experiment.” ICAR2001
[3] S. Doi, Y. Wakabayashi, T. Hosokawa, T. Sugano, “Control Aspect of Japanese Experiment Module Remote Manipulator System.” 1st IFAC
[4] N. Sato, S. Doi, “JEM Remote Manipulator System (JEMRMS) Human-In-the-Loop Test.” 22nd ISTS