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International Space Station Robotics: A Comparative Study of ERA, JEMRMS and MSS

Patten Laryssa[(1)], Evans Lindsay[(1)]
Oshinowo Layi[(2)], Ochisor Marius[(1)], Kazuharu Nara [(3)], Lodewijk Aris [(4)], Tabarah Ed[(1)]

[(1)]Canadian Space Agency
6767 route de l'Aéroport,
Saint-Hubert, Québec, Canada, J3Y 8Y9
Email: : laryssa.patten@space.gc.ca

[(3)]NASDA
2-1-1, Sengen, Tsukuba-shi,
Ibaraki 305-8505 JAPAN
Email: nara.kazuharu@nasda.go.jp

[(2)]MD Robotics
9775 Airport Rd
Brampton, Ontario, Canada
Email: layi.oshinowo@space.gc.ca

[(4)] Dutch Space B.V.
Newtonweg 1 Postbus 32070 2303 DB
Leiden, The Netherlands
*Email:*l.aris@dutchspace.nl

ABSTRACT

Robotic manipulators are essential for the construction and maintenance of the International Space Station (ISS). Manipulators will also be used to support experiments, extra-vehicular activity (EVA) and scientific activities onboard the ISS. The Canadian, Japanese and European Space Agencies are developing and delivering ‘robotic arms’, each with a specific role to play over the lifetime of the ISS. Each robotic manipulator has a unique design and task specific characteristics.

The Mobile Servicing System (MSS) is Canada’s contribution to the ISS. It includes the Space Station Remote Manipulator System (SSRMS), the Mobile Base System (MBS) and the Special Purpose Dexterous Manipulator (SPDM). The SSRMS is a 16.9 meter, 7 degree of freedom (DOF) manipulator with a relocatable base. It was launched successfully in April 2001 and within a year and a half, has installed the Airlock Quest, the MBS, and the first two truss segments (S0 and S1). SSRMS was designed to play a key role in the construction of the ISS. Canada's next robotic contribution to the ISS is a smaller, more dexterous two armed robot, the SPDM. It is scheduled for launch in Jan 2005.

The Japanese Experiment Module (JEM) Remote Manipulator System (JEMRMS) is one of the National Space Development Agency of Japan’s (NASDA) contributions to the ISS. The Main Arm (MA), a 9.91meter, 6 DOF manipulator, will be permanently attached to the JEM Pressurized Module (PM). More dexterous tasks will be accomplished using NASDA’s Small Fine Arm (SFA), also a 6 DOF manipulator which can be operated when grappled at the end of the MA. JEMRMS will be used to support experiments being conducted on the JEM Exposed Facility (EF) and to support JEM maintenance tasks. JEMRMS is currently scheduled to be launched in June 2006.

The European Robotic Arm (ERA) is an 11-meter, 7 DOF manipulator with a relocatable base intended for installing solar panels on the Russian Solar Power Platform (SPP), handling payloads and carrying out maintenance tasks. Unique to this manipulator is ERA’s ability to be operated by a crewmember from either inside or outside the ISS. ERA is currently scheduled to be launched in 2007.

INTRODUCTION

The ISS assembly, maintenance and scientific research tasks depend on the three robotic manipulators carrying out their intended operations. Each manipulator has a specific purpose and each has been designed to successfully complete its assigned mission. Currently, the ISS will be manned with three crew members only. This will require that the ground personnel, trainers, and mission controllers have an understanding of the operations and design of all of the station manipulators since it is likely that the same crew will operate all three manipulators. Furthermore, there are some handoff operations which require the operation of two station manipulators. Adding complexity, the control centres for each manipulator are located on different continents, JEMRMS in Japan, ERA in Russia and SSRMS in USA and Canada.

This paper presents the planned operations, design, operator interface and ground control of each manipulator. The similarities in manipulator architecture and design, as well as their differences, are discussed. It is written in four main sections. Initially there is an introduction to the operational tasks that each manipulator will perform, then the architectures of each manipulator is described, where the differences and similarities of each system are highlighted. Following this there is a short summary of the operator interface and concept of operations for each manipulator. Ground control capabilities of each system are discussed in the fourth section.

ON ORBIT OPERATIONAL TASKS

SSRMS Operational Utilization

The SSRMS is primarily used for ISS assembly. This involves acquiring an assembly payload, either directly from the Shuttle Payload Bay or handed off from the Shuttle Remote Manipulator System (SRMS). To date, the SSRMS has handled the Space Lab Pallet (SLP), Airlock, O_2-N_2 high-pressure gas tanks, S0 Truss Segment, MBS, and most recently, the approximately 12,600 kg S1 Truss Segment. The SSRMS is also used to manoeuvre astronauts and whatever they are holding from point to point as they complete their tasks during the EVA.

Until the recent completion of the STS-112 ISS-Shuttle mission, the only permanent external cameras available for viewing the ISS environment were located on the MSS. It would be a fair statement to say that these cameras have been very highly appreciated items on-orbit since the SSRMS was installed. The cameras have been used for observing Shuttle and ISS water dumps, inspecting solar panels for surface degradation, inspecting berthing interfaces for debris, and observing visiting vehicle docking and undockings (e.g. Shuttle, Soyuz, and Progress), in addition to the standard assembly and EVA -related tasks.

The SSRMS' tasks also include manipulating payloads that are specifically designed for logistics and re-supply purposes. These include the Italian Multi-Purpose Logistics Module (MPLM), which has only been handled by the SRMS to-date, and the Japanese Heavy Transfer Vehicle (HTV), a free-flyer vehicle, along with its Exposed Pallet containing Orbital Replaceable Units (ORU). Maintenance support activities are either EVA -based or Extra-Vehicular Robotics (EVR) based, i.e. the SSRMS will be used for positioning the SPDM, in order to replace externally located SPDM compatible ORUs.

The SSRMS has not been used for, or to assist with, scientific experiments to date. However, it is envisioned that it could be used in any number of ways including as a platform (i.e. an experiment is attached to it), to position an experiment in a particular position/orientation, or to periodically inspect an externally located experiment.

ERA Operational Utilization

The ERA will be used on the Russian segment (RS) of the ISS. Specific tasks for the ERA include installation and deployment of solar arrays and solar array drives (specifically the B-20 Solar Array Drive Assembly), replacement and servicing of solar arrays, inspection of the RS, ORU transfer and placement, as well as the transfer and support of EVA astronauts and cosmonauts.

It is envisioned that the ERA cameras will be used for inspection tasks of the ISS and possibly to monitor ISS activities such as water dumps. The internal ISS crew will position the ERA in a manner to enable viewing.

JEMRMS Operational Utilization

The JEMRMS is system used primarily for experiment payload handling. The MA will be used for capture/release and transfer of experiment payloads on the JEM Exposed Facility (JEF), JEM Experiment Logistics Module – Exposed Section (JLE), and exposed pallet of the HTV, communication with and providing power to captured payloads, capture/release and positioning of the SFA, and assembly of JEM modules (including JLE, JEF and JEM Experiment Logistics Module – Pressurized Section (JLP) and the exposed pallet of the HTV). The SFA will be used for capture/release, transfer, and maintenance of ORUs on the JEF and JLE, and communicating with and providing power to captured ORUs.

The operation of the MA is designed to reduce crewmember workload as much as possible since tasks include operations conducted over long periods of time such as payload transfer between the JLE and JEF from the MA storage position. Therefore, the MA operations tend to use automatic modes. However, the operations of the SFA including dexterous tasks, require a high degree of precision and positioning accuracy. Currently the JEM RMS on orbit use is estimated to be twice per year.

DESIGN DESCRIPTION – Physical Description and Components

All three ISS robotic manipulators are designed to resemble the human arm. They are mechanically and electrically connected to the ISS at the shoulder, which is comprised of a set of revolute mechanical joints. A boom segment and then an elbow joint follow the shoulder. After the elbow there is another boom segment followed by a set of wrist joints and an end effector through which the operational grappling is carried out.

SSRMS

The 16.9m SSRMS has 7 offset joints and is symmetric about the elbow with identical 3DOF shoulder and wrist clusters (Figure 1). The shoulder/wrist clusters contain three mechanical joints with perpendicular rotation axes: pitch, yaw and roll. One joint cluster acts as the shoulder while the other acts as the wrist of the manipulator. All of the SSRMS joints are functionally identical with the same performance capabilities and angular range of +/-270 degrees. The three pitch and two roll joints are identical and interchangeable. The two yaw joints are identical and interchangeable (the difference between the yaw and pitch/roll joints being that the yaw joints have a 5.25 inch extension non one end). Each of the joints is an ORU and each contains two identical joint electronics units and motor modules.

Attached to the roll joint on each cluster is a Latching End Effector (LEE) which provides a mechanical and electrical connection to a payload, SPDM or the ISS when grappling an SSRMS grapple fixture. Each LEE also includes a Force Moment Sensor (FMS) and two identical LEE Electronics Units (LEUs). This symmetric configuration allows either end of the SSRMS to be attached to a Power and Data Grapple Fixture (PDGF) and to function as the base of the arm.

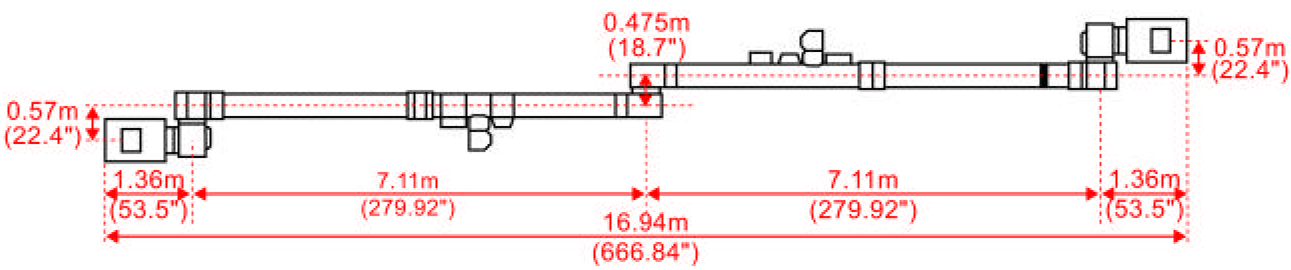

Figure 1: SSRMS Dimensions

The SSRMS has two camera/pan and tilt units located on the booms of the SSRMS and fixed view, "bore-sight" cameras on each LEE. These cameras are intended to aid the operator with situational awareness when manoeuvring the manipulator, when grappling and when performing inspection tasks. Identical arm computer units (ACU) are also located on each the booms of the SSRMS.

ERA

The ERA manipulator arm spans 11.3m and has 7 inline joints in a symmetric configuration with respect to the elbow joint (Figure 2). It has a shoulder with 3 DOFs, an elbow with 1 DOF and a wrist with 3 DOFs. Both the shoulder and wrist contain three functionally identical joints with mutually perpendicular rotation axes. An electronics box containing the prime and redundant electronics for the wrist/shoulder clusters is located between the cluster pitch joint and the boom segments. A single elbow joint electronics box is located on one side of the elbow pitch joint and the ERA control computer is located on the other side of the joint. The operational joint limits of the ERA are listed in Figure 3.

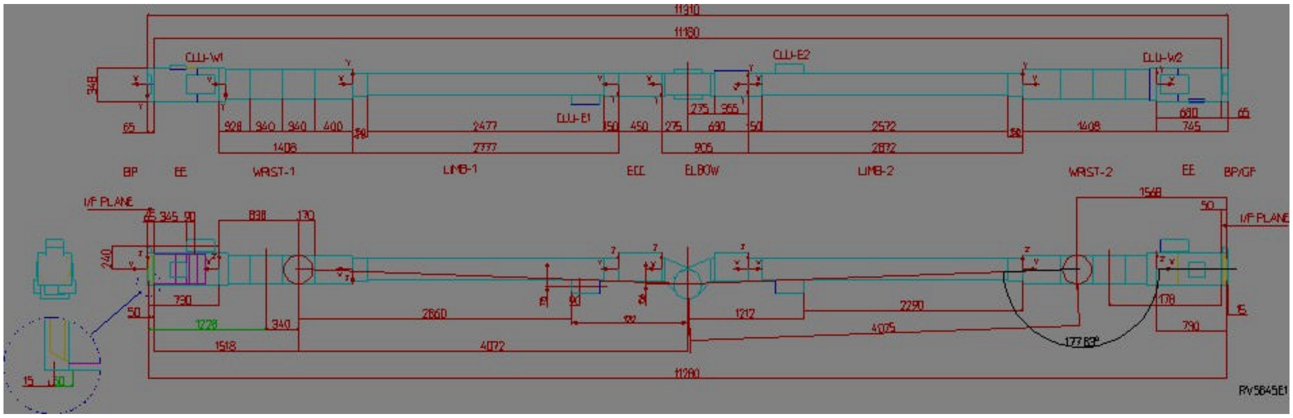

Figure 2: ERA Dimensions

The ERA has two end effectors (EE) which can act as a base, enabling either end of the ERA to be used as the shoulder Thus the wrist and shoulder are operationally interchangeable, just as in the SSRMS design. The identical EE’s are able to grapple and ungrapple an ERA grapple fixture, transferring power or data to an external device/load. The EE also has an Integrated Service Tool (IST) which is a built-in motorized "screwdriver" that can provide mechanical torque actuation.

The ERA is equipped with four Camera and Lighting Units (CLU) one on each EE and one on either side of the elbow. The CLU will be used to provide video images of operational tasks and, if necessary, to illuminate the scene and to act as an optical sensor to enable proximity control of a target during approach of a basepoint or grapple fixture in closed loop. The proximity control function enables ERA to approach grapple fixtures automatically and smoothly.

	SSRMS (°)	SPDM (°)	ERA (°)	JEMRMS MA (°)	JEMRMS FINE ARM (°)
Shoulder Roll	±270	±180	± 185	N/A	N/A
Shoulder Yaw	±270	- 85 / +130	± 120	-100 / +80	+90 / -90
Shoulder Pitch	±270	±180	± 120	- 60 / +210	+105 / -105
Elbow Pitch	±270	±155	+30/-176	-175 / +175	+65 / -90
Wrist Pitch	±270	-215 / +90	± 120	-180 / +90	+100 / -170
Wrist Yaw	±270	-95 / +130	± 120	-240 / +90	+90 / -180
Wrist Roll	±270	±180	± 185	-215 / +215	+120 / -120

Figure 3: SSRMS, SPDM, ERA , and JEMRMS Joint limits

JEMRMS

The JEMRMS main arm is a 6DOF manipulator arm and is attached to the outer side of the JEM Pressurized Module (JPM) end cone. It has 2 DOFs at the shoulder (yaw and pitch), 1 DOF (pitch) at the elbow and 3 DOF (pitch, yaw, and roll) at the wrist. Each offset joint is driven by an electric motor with a dedicated joint electronics unit in the mechanism. There is a single joint electronics unit located in each JEMRMS joint and the arm control unit is located within the JEM pressurized module. A diagram with dimensions of the JEMRMS is shown in Figure 4, and the joint ranges for the JEMRMS are listed in Figure 3.

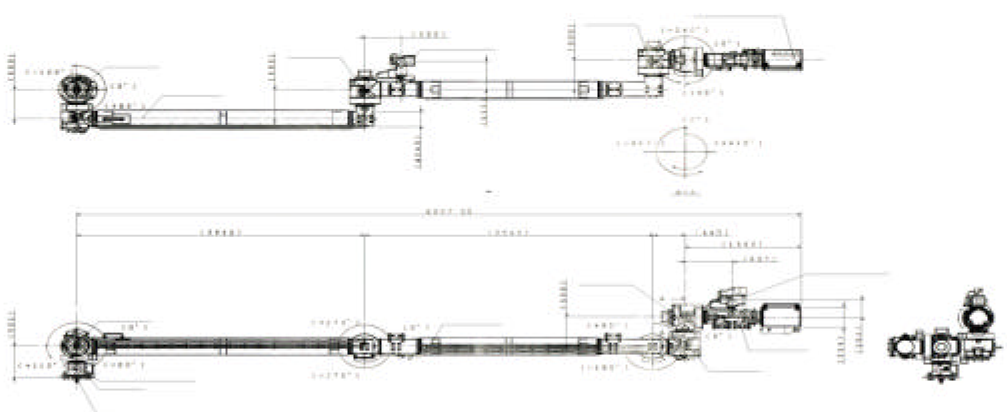

Figure 4: JEM RMS Dimensions

In addition to the fixed base design, another difference between the MA and the SSRMS and ERA is that it has a third boom, which joins the wrist roll joint to the end effector.

To provide situational awareness, there are two cameras located on the JEMRMS elbow and wrist. The elbow vision equipment includes a TV camera and a pan and tilt unit while the wrist also has an extra light unit. There is a window in the JEM airlock, which the operator can use for 'snapshot' situational awareness since this window cannot be reached from the JEMRMS workstation.

The JEM RMS end effector was designed based on the Shuttle RMS (SRMS) end effector. The grapple fixtures compatible with the JEMRMS MA can also be grappled by the SSRMS. Using the JEMRMS vision equipment it is possible for the JEMRMS to perform automatic captures using a ranging function. . (Note: the ranging function is also used for payload berthing onto JEF) This effector also provides a mechanical and electrical connection to a payload or the SFA.

Specifications

A subset of the performance specifications of the three manipulators is provided in Figure 5. Both the ERA and the SSRMS are designed to work in large workspaces and their 7DOF, relocatable base design enables this, whereas the JEMRMS is dedicated for work on the JEM EP, a smaller workspace. Having offset joints on the SSRMS adds some complexity to operator and mission planning tasks, always having to be aware of collisions between the joints, but it also enables the SSRMS to manoeuvre more readily over large areas by "stepping over the elbow".

	SSRMS	ERA	JEMRMS (MA)
SPAN	14.22m	11.3m	9.91m
Boom Span	7.11m	7.77m	3.93m and 3.94m
DOFs	7	7	6
Joints	Offset	Inline	Offset
Base	Relocatable	Relocatable	Fixed
Positioning Accuracy	65mm, 0.71deg	40mm, 1deg	50mm, 1.8 deg
Mass	1336kg	630kg	757kg
Stopping distance (no p/l)	610mm 3deg	160mm	300mm, 5deg
Max Handling Capacity	116, 000 kg	8000kg	7000kg
Power Consumption	1360W (average)	>800W	2.3kW
Translation	370 mm/sec 150 mm/sec (1000kg) 20 mm/sec (20900kg) 12 mm/sec (116000kg)	200mm/s 150mm/s(100kg) 40mm/s (3000kg) 10mm/s (8000kg)	60 mm/sec (600kg) 30 mm/sec (3000kg) 20 mm/sec (7000kg)
Rotation	4.0 deg/sec 1.2 deg/sec (1000kg) 0.15 deg/sec (20900kg) 0.04 deg/sec (116000kg)	3deg/s 2.3deg/s (100kg) 0.6deg/s (3000kg) 0.15deg/s (8000kg)	2.5 deg/sec (600kg) 1.0 deg/sec (3000kg) 0.5 deg/sec (7000kg)

Figure 5: SSRMS, ERA and JEMRMS Specifications

The 7DOF design of the European and Canadian arms provide an extra degree of freedom that will enable both manipulators to access tight workspaces and avoid ISS structure during operations. This is particularly important when working in areas that have exposed station structure. The 7th DOF also allows for Arm Pitch Plane Change manoeuvres to avoid structure without changing the end effector position.

The maximum handling capacity also dictates the type of payloads the manipulators can grasp. The SSRMS is capable of handling payloads that have an equivalent mass to the Orbiter. The ERA is designed for slightly smaller payloads such as solar panels.

The ERA and the JEMRMS provide much finer position accuracy than the SSRMS – smaller payloads require more precise alignment. Also, the force moment sensor is always used for ERA and JEM operations and is optional for SSRMS operations. This FMS capability facilitates "peg in the hole" type of operations.

DATA and POWER ARCHITECTURE

SSRMS

The SSRMS power and data architecture (Figure 6) is characterised by two electrically independent channels each fully capable of performing electrical functions of SSRMS.

SSRMS is powered through the PDGF/LEE interface and power distribution is comprised of two payload designated power buses, and two SSRMS user power buses. The user power bus provides power to the SSRMS components that

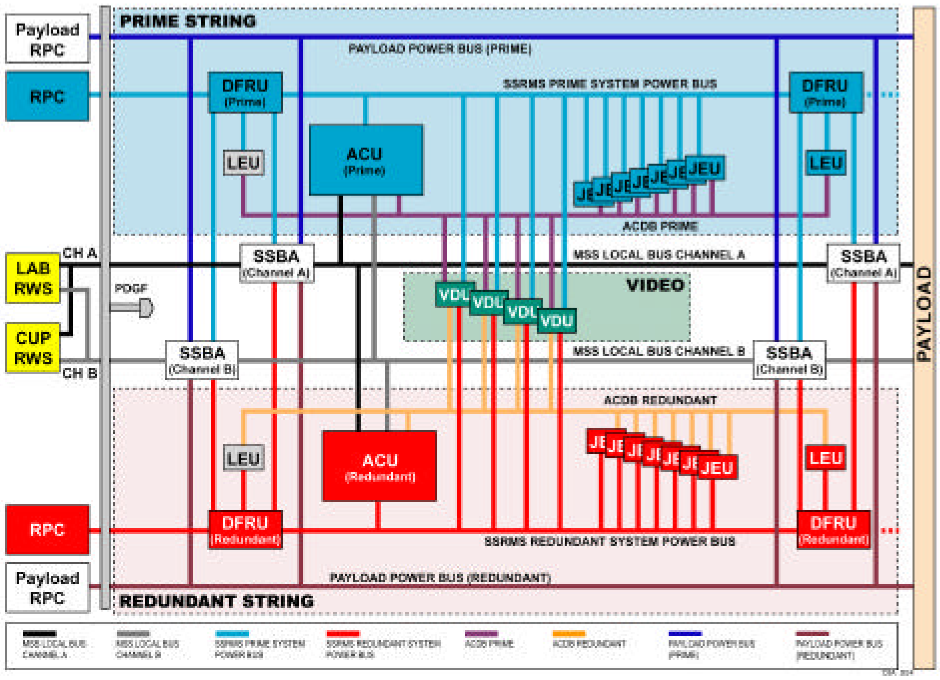

Figure 6: SSRMS Architecture Diagram

are connected in parallel along the bus. The power buses are designed to prevent the propagation of failures along the bus by having independent on/off control. The video distribution units are cross-strapped to both the prime and redundant SSRMS power buses and there is no redundancy in these units.

The data for SSRMS operation is distributed along an external data bus to the ISS PDGFs via the PDGF Local Bus, or to four MBS PDGFs located on MBS via the MSS Local Bus. The internal data distribution is independent of the SSRMS base location. The SSRMS ACU interfaces to these external databases as a Remote Terminal and also acts as a Bus Controller for the internal arm databus. The SSRMS ACU performs the kinematic transformations and management necessary to command the joints and LEE in real time via their respective electronics units the JEU and LEU.The data interface to ISS is through two MIL-STD-1553B data buses which pass through the SSRMS from one end to the other. There are two sets of independent, identical electronics boxes where, the prime equipment is only connected to the prime internal SSRMS bus (ACDB) and controlled by the prime ACU. The redundant equipment is similarly connected to the redundant internal bus. If a failure occurs on one power or data string in the SSRMS the operator will have to manually switch to the remaining string.

An operator sends commands from a robotics workstation located inside the ISS. These commands are sent to the main MSS computer and then after processing by the main computer, along the external bus to the ACU for processing and disseminating along the internal databus to JEU, LEU or video distribution units for execution.

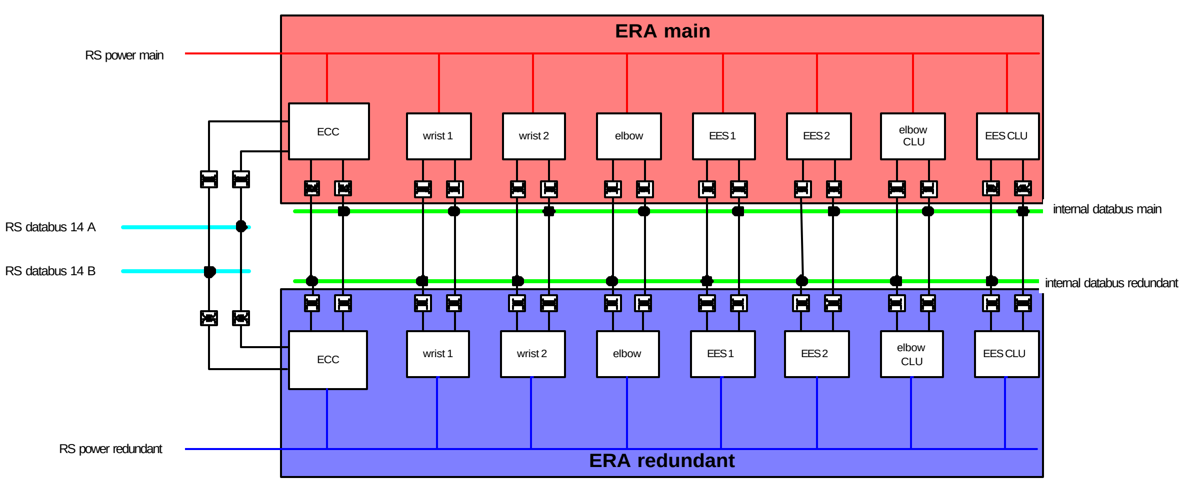

Figure 7: ERA Power and Data Architecture

ERA

The ERA power and data architecture also provides complete electrical redundancy, although slightly different from that of SSRMS. Please refer to Figure 7 for a graphical representation of the ERA architecture. Power is supplied to the ERA from the Russian Segment (RS) via the manipulator basepoint. The power lines run along the arm from one EE to the other and all electronics units are individually connected to these power lines but are switched on and off as a group. There are two sets of three independent power lines; the ERA electronics power, required to operate ERA, ERA thermal control power, and payload power which can each be individually controlled. Having two sets of independent power lines makes the ERA power architecture completely redundant.

The ERA commands and data flow along two main buses, the external bus, and internal arm bus. Commands are sent to the ERA Control Computer (ECC) via the external bus, from the operator, who can be commanding via the External Man Machine Interface (EMMI) or the Internal Man Machine Interface (IMMI). The second communication bus is the internal arm bus, which communicates between the ERA ECC and the ERA subunits. Payload commands are sent along the internal databus. The data communication is based on a MIL-STD-1553 architecture where ECC is the bus controller for the internal bus and the central processing computer (CPC) is the controller for the external bus; all other subunits are remote terminals.

The Internal bus is hot-redundant, meaning that the ECC and ERA subsystem can communicate over either bus without requiring special reconfiguration. When the ECC is powered on, it checks the health of both internal buses. The ECC communicates with the ERA subunits, each joint, end effectors and the CLU's. The ECC communication bus is subunit dependent. If one unit fails to communicate on bus A, then the ECC will communicate with the particular unit on bus B while the remaining units will be communicating on bus A. The switch is automatic and invisible to the operator.

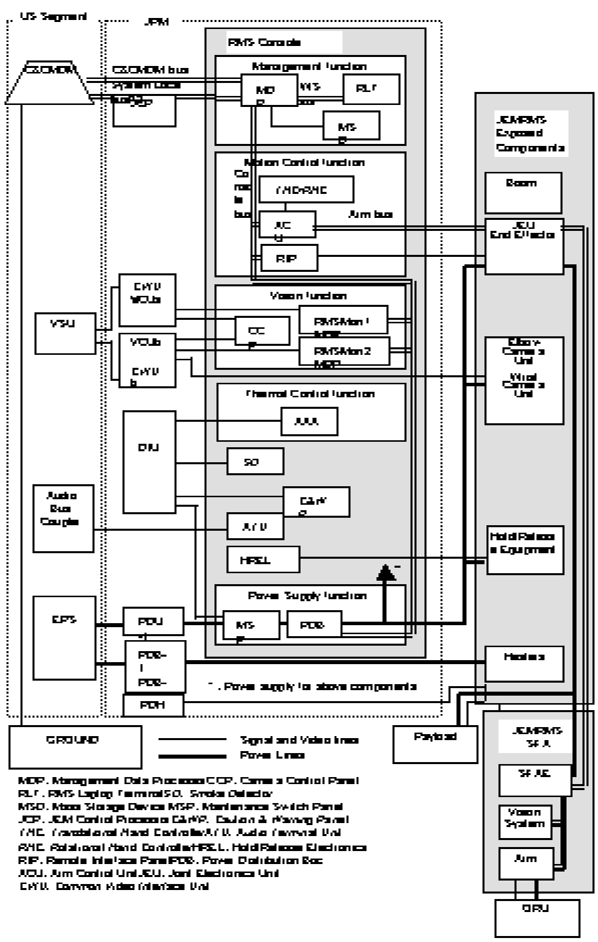

Figure 8: JEM RMS Power and Data Architecture

During EVA control of the ERA, the EMMI is connected to one of the ERA basepoints through which it receives power (27V) and is connected to the ERA External 1553 bus. The EMMI can also be powered from the ERA payload bus via a dedicated payload on the EE and, for monitoring purposes only, can be connected to the ERA internal databus. The EMMI can be connected to one of two connectors on the basepoint and each connector contains a connection to both databuses.

JEMRMS

The JEMRMS has a single set of electrical and mechanical components and hence does not have complete electrical system redundancy. It obtains station power through the Power Distribution Box (PDB) in the JEMRMS console. This powers the components in the console and provides heater power to all exposed components, although there are two PDB's which can provide power to the JEMRMS components, as stated earlier, there is only one set of components.

The data architecture of the JEM RMS is similar to that of the ERA and SSRMS but without data communication redundancy. It also uses a MIL-STD-1553B bus and has internal and external data buses. The internal bus communicates between the ACU (located in the JEM PM) and the joint electronics units (one per joint), end effector electronics unit and the video units. The external databus handles communications between the ACU and the operator workstation. Please refer to Figure 8 for a graphical representation of the JEM architecture.

MANIPULATOR CONTROL

The ERA is the only manipulator that can be controlled by an EVA, beyond contingency operations e.g, driving a joint with a tool. An operator can command the ERA from a man machine interface that is either internal (IMMI) or external to the station (EMMI). The EMMI has toggle switches which the EVA can use to command the ERA in manual mode, single joint mode or to command the next step in an auto sequence. It also provides status back to the operator. The ERA manual commands include operator inputs to control the end effector motion in a single axis motion at time. Multi-degree of freedom inputs cannot be made from the EMMI unless they have been pre-programmed in an auto sequence. The EMMI operator can also command a single joint to move at a time. The IMMI has all the features and capabilities of the EMMI with an additional laptop interface that provides a synoptic display of the current position of the ERA and other status information.

The ERA designers have included a number of features which aid the EVA and the internal station operator. Firstly, the ERA has an algorithm which detects the ERA proximity to structure and will stop the ERA before it can collide with structure. This algorithm depends on having an up to date ISS model. Secondly, grappling is performed automatically with a combination of laser sensing by the CLU for coarse alignment and a torque moment sensor on the ERA EE aiding the fine alignment. This allows automatic smooth grappling and un-grappling. A similar feature is available on the JEMRMS

Both the SSRMS and JEMRMS are controlled from dedicated workstations within the ISS (the SSRMS has a backup workstation). Both manipulators can be controlled using translational and rotational hand controllers. These two manipulators are ‘flown’ by the operator usind hand controllers and require more crew skill and dexterity. The operator commands the end effector motion and depends on camera views for situational awareness. This requires a higher level of training and skill from the operators and allows more room for operator error. Similar to the ERA, the JEM and SSRMS can be controlled via autosequences and joints can be operated individually when needed.

Having an extra degree of freedom on the ERA and SSRMS offers many options for trajectory planning. It also means that there is an infinite number of solutions for any given EE position. This is undesirable when planning manoeuvres that would bring the manipulator close to structure. A completely predictable trajectory is needed. The ERA designers have designated a nominal operation with the shoulder yaw locked, while the SSRMS allows the mission designer or operator to choose which joint to lock.

GROUND VERSUS CREW INOVLVEMENT

All three systems have been designed to allow the on-orbit operator to have complete control over each manipulator with the ground monitoring the activities. However, the amount of control the ground has over each manipulator is quite different. The SSRMS and JEMRMS can be powered from the ground, the cameras can be controlled and the ground can initiate diagnostic tests. At present, the ground cannot perform any action that initiates SSRMS or JEM RMS manipulator motion since the ground cannot issue a ‘remove brakes’ command. However once the brakes are removed on the JEM RMS it can be controlled form the ground. At present, the SSRMS cannot. Similarly the ground cannot command any motion of the ERA. In fact, the ERA telemetry is not seen in real time on the ground; it is downloaded at a later time. This empowers the ERA on-orbit operator to do any initial troubleshooting and decision making for critical operations. Hence, the level of operator autonomy and responsibility is higher for the ERA operator, as it is up to the operator to ensure that the mission is completed, including possible troubleshooting for malfunctions. The SSRMS and JEM RMS operator has a higher dependence on ground support to help with contingency planning during malfunctions. In fact for JEM RMS operations there are not tasks envisioned which would require an immediate quick response from the crew.

CONCLUSION

All three ISS manipulators, SSRMS, ERA and JEMRMS have been designed to successfully complete their specific on orbit tasks. There are many similarities and differences in the design and the operator interfaces of each manipulator. Together the three manipulators will be permanently on the ISS and will provide users with ISS maintenance, re-supply and scientific experiment capabilities.