INTERNATIONAL SPACE STATION ROBOTIC SYSTEMS OPERATIONS – A HUMAN FACTORS PERSPECTIVE

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Assembly and maintenance of the International Space Station (ISS) relies heavily on the use of extra-vehicular robotic systems. When fully assembled the ISS robotics complement will include three main manipulators, two small dexterous arms, and a mobile base and transporter system. The complexity and mobility of the systems and limited opportunities for direct viewing of the Space Station's exterior makes telerobotic operations an especially challenging task. Although fundamental manipulator design, control systems, and strategies for autonomous versus manual control vary greatly between the systems, commonality in the design of workstation controls and displays is considered essential to enhance operator performance and reduce the possibility of errors. Principal human factors opportunities are associated with workstation layout, human-computer interface considerations, adequacy of alignment cues for maintenance of safe approach corridors during mating tasks, spatial awareness challenges, integration of supplemental computer graphic displays to enhance operator global situational awareness, and training methodologies for preservation of critical skills during long-duration missions.

INTRODUCTION

When complete, the ISS will be the largest and most complicated spacecraft ever assembled. Five international space agencies - National Aeronautics and Space Administration (NASA), Russian Space Agency (RSA), Canadian Space Agency (CSA), National Space Development Agency of Japan (NASDA), and European Space Agency (ESA) - have developed the suite of robotic systems. Control of robotic systems in microgravity is a delicate and risky activity. The complexities are related to large masses (> 100,000 kg.), multi (6 and 7) degree-of-freedom systems, distinctive end effectors, limited direct visual information, diverse manual and automatic control conditions, Extra-vehicular activity (EVA) and Intravehicular activity (IVA) interfaces, and very high potential costs of error. Safe and efficient robotic operations require crewmembers to possess unique coordination and manipulation skills and detailed knowledge of the system's design and operation. Ensuring commonality between the systems will contribute to increases in mission success probabilities, expand safety margins of critical operations, and minimize system-specific training. Although commonality considerations were paramount during the design phase of these systems they were also weighted with respect to the flexibility and adaptability of individual system designs, design costs, and schedules.

Overview of Manipulator Systems

ISS robotic systems are comprised of a mix of manipulators with unique control systems and algorithms, capabilities, and flying characteristics. Space robotic system design features intended to optimize human and automatic control activity include: trajectory and motion limitations; collision avoidance algorithms; automatic safing schemes; force moment accommodation; and integrated procedures involving automated, ground, and crew control.

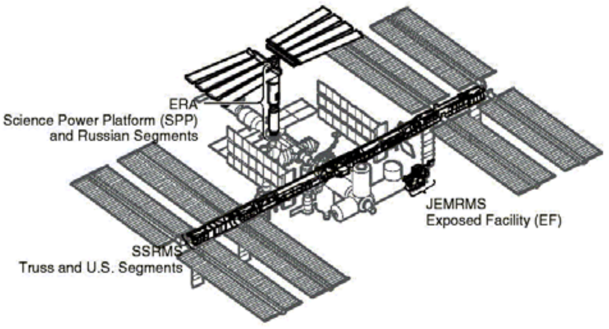

Figure 1: Locations of ISS Robotic Systems

Mobile Servicing System (MSS) (Fig 2). Jointly developed by Canada and NASA, the MSS will primarily function on the U.S. segments and truss assembly. It is comprised of five subsystems – the Space Station Remote Manipulator System (SSRMS), the Mobile Base System (MBS), the Mobile Transporter (MT), the Special Purpose Dexterous Manipulator (SPDM), and the Robotic Workstation (RWS). The SSRMS is a 17-foot long manipulator consisting of two booms, seven joints, each with a range of ±270°, and two latching end effectors. Power, data, and video are provided to the payloads via the latching end effectors. During assembly, the SSRMS will primarily be used to install pressurized modules and truss elements. The SSRMS can operate from any power and data grapple fixture on the ISS, giving the SSRMS the capability of "walking" or repositioning itself to a new base point. Control and monitoring of the SSRMS is from one of two modular workstations, both initially deployed in the US Laboratory module. The RWS components are portable and include three video monitors, two hand controllers – one to effect translation and one for rotational inputs, a Display and Control panel, a Portable Computer System (PCS), and a cursor control device.

The SPDM is a dexterous manipulator with two symmetrical seven-joint arms attached to a central body structure. Its primary function is the changeout of robotically compatible small equipment on the Space Station's exterior. Additional SPDM tasks include scientific payload servicing and inspection and monitoring in support of extravehicular activities (EVA). The SPDM can either be operated from the end of the SSRMS or as a stand-alone manipulator system.

The MT provides transportation of the SSRMS along the exterior ISS truss. At its maximum velocity of 2.54 cm/sec, it will take 50 minutes to traverse the entire length of the truss when the ISS is fully assembled. The high mass/inertia, costly payloads, and great vulnerability of space vehicles to mechanical damage associated with space operations require very slow translation speeds to avoid overruns, reduce oscillations, and prevent collisions. These slow translation speeds require significant levels of operator vigilance.

The MBS provides a mobile base of operations for the MSS and serves as an interface between the MT and the SSRMS. It functions both as a work platform and as a base for the manipulators. The MBS provides four interfaces to support attachment of the SSRMS and the SPDM and provisions for power and temporary storage of payloads and Orbital Replacement Units (ORUs).

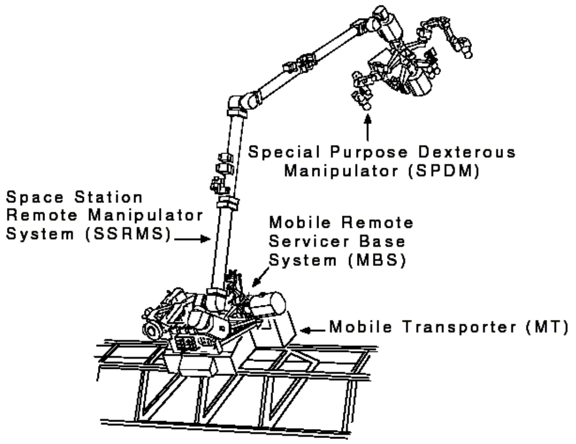

Figure 2: Mobile Servicing System

The Japanese Experiment Module Robotics System (JEMRMS) (Fig 3). Developed by the National Space Development Agency (NASDA) of Japan, the JEMRMS is primarily intended for use on the JEM Exposed Facility (EF). This system is comprised of two manipulator devices, the Main Arm and the Small Fine Arm, and the JEMRMS console. The Main Arm is a 10-meter long, fixed-base, six-joint robotic arm with two main booms. The Small Fine Arm is a 2-meter long dexterous manipulator consisting of six joints, two booms, and an end effector mechanism. The Small Fine Arm can only be operated from and relocated by the Main Arm. The JEMRMS Console is located inside the JEM Pressurized Module and provides manual augmented, autotrajectory, and single-joint modes. Two different operational schemes are planned for the two JEMRMS manipulators. Control of the Main Arm will be primarily through the use of semi-autonomous autotrajectories designed to reduce crew workload since planned tasks include long and tedious operations (payload transfer). A manual control mode will be used most frequently for Small Fine Arm operations, which are primarily dexterous tasks requiring high positioning and trajectory accuracy.

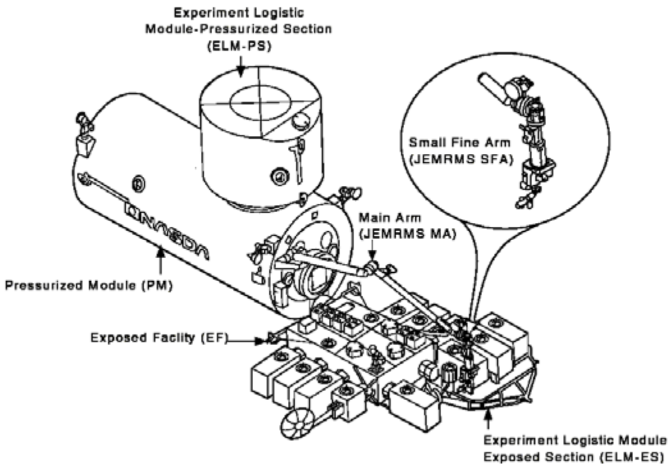

Figure 3: JEM Manipulator Systems

The European Robotic Arm (ERA) (Fig 4). The ERA, built by the European Space Agency (ESA) under contract from the Russian Space Agency (RSA), is an 11-meter manipulator with seven joints and two booms. It will primarily perform automated operations. The ERA manipulator also has "walking" capability but can reposition only to base points located along the Russian Segment. Operational control is either through an EVA Man-Machine Interface (EMMI) or through an IVA Man-Machine Interface (IMMI), when the operator is inside the Russian Service Module. It is the only ISS manipulator that does not include hand controllers. Control will primarily be through an autotrajectory mode, but manually selectable single-joint modes are also available.

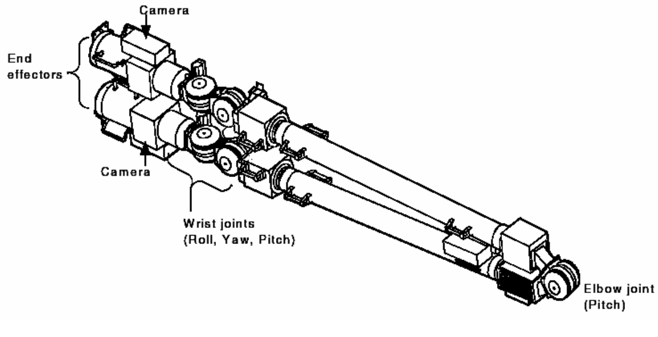

Figure 4: European Robotic Arm

Table 1 provides a comparative analysis of the respective characteristics of the ISS robotic manipulator systems.

System	Mobile Servicing System		JEM RMS		ERA
	SSRMS	**SPDM**	**Main Arm**	**Small Fine Arm**	
Primary Function	ISS assembly/ maintenance, payload retrieval and handling, EVA Support	ISS maintenance, small payload handling	JEM Exposure Facility payload handling	JEM Exposure Facility payload and ORU handling	Russian segment maintenance, EVA support
Joints	7	15 (7/arm + 1 body)	6	6	7
Manipulator Length	17m	3.5 m	10 m	1.7 m	11.2 m
Max Payload Mass	116,000 kg	600 kg	7000 kg	300 kg	8000 kg
Operation Modes	Manual, Automatic, Single Joint	Manual, Automatic, Single Joint	Manual, Automatic, Single Joint	Manual, Automatic, Single Joint	Automatic, Single Joint
Max Arm Speed	0.36 m/s 4.0 deg/s	0.075 m/s 2.5 deg/s	0.06 m/s 2.5 deg/s	0.05 m/s 7.5 deg/s	0.2 m/s 2.9 deg/s

Table 1: Manipulator System Characteristics

HUMAN FACTORS CONSIDERATIONS

Designs that optimize operator interfaces to the ISS robotic systems are key to enhancing operator performance and decreasing potential human errors during critical assembly and maintenance operations. Principal considerations include workstation topography and design, including mechanisms to assist with operator orientation and stabilization; graphical user interface commonality within and between systems; adequacy of alignment cues for maintenance of safe approach and mating corridors during berthing tasks; spatial awareness challenges; integration of supplemental computer graphic displays to enhance operator global situational awareness; and methodologies to preserve critical skills during long-duration missions.

Control Interfaces

Workstations should be designed to allow for emergency intervention by operators through hardware rather than software interfaces. It is clumsy and potentially hazardous to require an operator to negotiate through several layers of software to effect an immediate action to stop the manipulator. Further, numerous malfunction scenarios can render the portable computer system inoperative. Common hand controller designs will reduce operator training, enhance positive habit formation, and reduce the potential for inadvertent or errant commands during manual manipulator control. Although it is ideal to have two crewmembers available to operate the system, provisions should be made for both single and multi-crew access for manipulator, camera, and support equipment operation. Postural stability and comfort is essential for extended duration operations (more than 7 hours), delicate and high stress activities - this is achieved by the design of restraint systems that accommodate a full spectrum of expected users and activities.

The MSS RWS (Fig 5) and JEMRMS Workstation (Fig 6) have very similar topography. For each system the central operator interface is a portable computer system, located in the center of the workstation. Two hand controllers, each providing three degree-of-freedom manipulations, are positioned adjacent to the computer interface. The hand controller located on the left side of the workstation provides translational manipulator control (fore/aft, left/right, up/down). The hand controller on the right side provides rotational control of the manipulator's end effector (pitch, yaw, roll).

Each of the workstations provides multiple television views and includes hardware switches/buttons for controlling the cameras associated with each system. When fully assembled the ISS will have fourteen different locations where cameras can be installed. There are also cameras located on each of the manipulators.

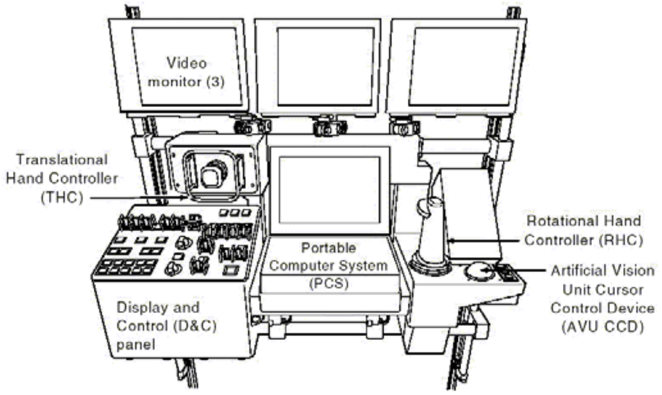

Figure 5: Mobile Servicing System Robotic Workstation

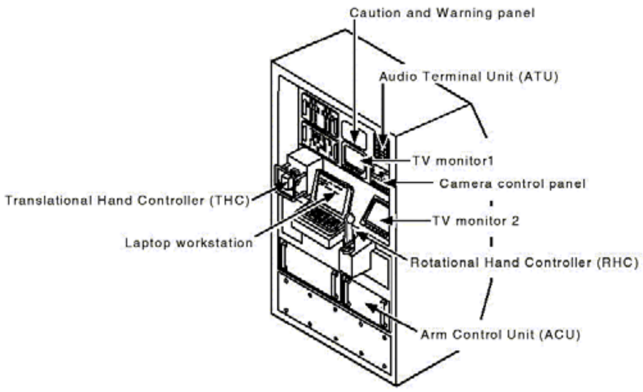

Figure 6: JEM Remote Manipulator System Console

Graphical User Interface Commonality

The graphical user interfaces, icons and procedures have to be readily understood by multinational crewmembers. The ISS Program Display and Graphics Commonality Standard documents the standards and guidelines utilized in design and implementation of displays and graphical products used by both the onboard crew as well as ground control centers. These standards are used in the development of onboard crew displays, reference drawings, and other graphical reference material. It is imperative for nomenclature and graphics used in robotics procedures to exactly match those used on the respective displays.

The presentation of joints and segment position and attitude information on robotics displays is consistent. The joints are arranged in order of their physical location in the manipulator, starting with the base. Starting from the left side of the graphic, each major component appears in the same order as on the actual manipulator hardware. The arm booms are further labeled with “Base” and “Tip”, particularly important for manipulators that have the capability to swap base ends during “walking” maneuvers. Operation-critical component feedback on the displays includes base location (if applicable), joint angle data, end effector/tool status, payload identification and/or status, and command and display coordinate systems.

Specific display and graphic colors were developed in accordance with industry and international standards and each color has a specific operational meaning. Some key colors used on robotics systems displays are red, yellow, and orange. A red color is used to alert the operator to pay immediate attention to the robot motion in order to avoid a potentially catastrophic event. Yellow indicates an out-of-limits condition or warrants operator attention to the robot motion in order to avoid loss of time. Orange denotes that the robot arm or hardware is in motion, or ready to be commanded into motion. It is also used to notify the operator that the corresponding hardware switch will cause motion when that switch is selected (a switch in this state is referred to as “hot”).

Colors are not used as the sole means for identification of the status of a component or subsystem. Alternate cues include labels, telemetry, or other graphical changes to acquire the attention of the operator. In some cases the background color of each robotics system are tinted to differentiate systems that are similar in content. For example, since the SPDM has two identical manipulator arms, the "general" SPDM pages have a gray background while the Arm1 and Arm2-specific manipulator pages are pink and green, respectively.

Robotics-unique attention indicators (annunciators) are used on displays and appear only when the operator’s immediate attention to the system is required. To facilitate proper operator scan techniques, these indicators are replaced by “place holders” when the attention-required event is not occurring. For example, one of the SSRMS attention indicators is used to alert the operator of an impending self-collision (one part of the robot is in close proximity to another part, and a collision would occur if motion in the same direction is not stopped). Although the manipulator control software, if enabled, should prevent actual contact of the manipulator components, it is important for the operator to note when they are approaching regions in which this may occur. Even if a self-collision event is not imminent, the rectangle and text containing the attention indicator is still distinguishable to the operator. Both color changes and flashing of the indicator are used as mechanisms to attain the operator’s attention in the self-collision warning region. If the region is further encroached upon, the software will automatically transition the manipulator into a “hold” mode and will accept no further operator inputs. At this point the indicator will transition to steady yellow and a black border appears around the rectangle.

Alignment Cues

Many of the mechanical systems used on the ISS for assembly and maintenance operations require precise alignment. During mating and berthing operations a safe corridor must be maintained by operators to prevent contact of the element, payload, or manipulator with surrounding structures. More important than the physically constrained “hardware” corridor is the narrower “operational” corridor that the operator must remain within for safe operations. Operational corridors are derived from actual hardware corridors and further modified or biased for ancillary items that can affect the accuracy of the target or alignment system. Allowances must be made for camera/target location and mounting precision complicated further by thermal, vibration and pressure influences. Target design characteristics and imperfections and the operator’s viewing angle of the scene can further impact total system accuracy. The familiar Fitts law challenges of target characteristics are paramount and the arm operators are always conservative in their speed/accuracy tradeoff - accuracy requirements dominate.

Alignment cues are dependent on lighting and shadow conditions and operations timing is enhanced by support from earth based lighting models. Lighting (natural and supplemental) and shadow conditions are sometimes so extreme to cause interference with human and automatic sensing systems. Ground support to model the anticipated lighting conditions has proven extremely useful in the planning of robotic arm operations. Key status indicators such as “ready to latch” micro-switches provide integrated mechanical system support and can be used to assist in achieving final mechanism alignment.

Spatial Awareness Challenges

The understanding and application of coordinate frames is essential for manual modes of operation and sustained attention during automatic modes of operation. During manual operations the operator must understand along which axis the arm tip or payload will move and around which point in space it will rotate. Several coordinate frames are used to support manual operations of ISS manipulators and to generate digital position and attitude displays. Fundamental elements are the Frame of Resolution (FOR), the Display Frame, and the Command Frame. The FOR defines the manipulator or attached payload multi-dimensional position (x, y, z) and attitude (pitch, yaw, roll). The Display Frame is the reference coordinate frame for the FOR to compute and display the position and attitude. The Command Frame determines the direction of motion of the arm/attached payload when hand controllers are used in a manual mode.

The selection of desired FOR, Display Frame, and Command Frame is a contributing factor in determining the degree of difficulty of a robotics task. The position of the manipulator or attached payload with respect to a base structure, vector of arm maneuver, and available visual cues are the major factors in determining the optimum combination of these coordinate frames.

Supplemental Displays

The operator's situational awareness is dependent on multiple cameras and derived digital information sources. Field of view, reference frames, and dynamically changing conditions make high demands on the operator's ability to comprehend current status and determine implications of the next control input. During the initial stages of ISS assembly there are limited external cameras available and almost no opportunities for direct viewing of the work site. Camera sources include zoom features that provide both global views and precise local information. Operators frequently must rely on cameras that are mounted on the manipulator itself resulting in a constantly changing point of reference as the task progresses.

Artificial or augmented reality cues, particularly bird's eye views, can be useful assist devices to enhance the operator's situational awareness. While supplemental views can be helpful they also add complexity to the operator's mental model of the progress of a robotic arm task.

Preservation of Critical Skills During Long-Duration Missions

Organizational design and operator training are key to mission success. One-gravity simulations are very helpful training aids but will never substitute completely for on-orbit experience. ISS crews are trained to perform the major assembly tasks that are scheduled to occur during their increment and are also trained in generic robotics skills as well.

Allocation of functions among long duration ISS crewmembers, short duration visiting Space Shuttle crews, and ground control is a developing science, based on the limited mission experience available. There are relatively few simulators available outside the US and limited skill-based training opportunities for crews in space. Training efforts are continually being improved through the use of video and computer-based techniques, simulators, and experienced expert advisors. Of particular importance in this organizational context is the provision of “just in time training” for tasks to supplement the robotics training that is only one part of a much more extensive mission training program, much of which is currently undertaken in Russia, away from U.S. and Canadian robotic arm training facilities.

On-orbit training is necessary to maintain the high level of proficiency necessary for safe and effective robotics operations. This real-time training has recently included video teleconferences with Mission Control to discuss task procedures, planned operations, and operational impacts and workarounds in response to systems failures. Training videos and computer-based training systems have been uplinked or provided to ISS crews by visiting Space Shuttle crews.

The design of systems for future long duration space missions should include provisions for operating the actual system in a “simulation” mode. Although there are drawbacks to this approach - notably the increased use of associated systems that could, in turn, impact failure incidence - stowage concerns for these extremely long duration missions will dictate the optimum use of all available onboard equipment.

CONCLUSION

In conclusion robotic arm operations are key to the assembly and maintenance of the International Space Station, to the transfer of materials from the Space Shuttle, and the deployment, capture, and maintenance of satellites. When fully assembled the ISS will have multiple extravehicular robotic systems, with different characteristics and a vast array of objects to be transferred, including EVA astronauts. The work is difficult, delicate, and dangerous. Human Factors contributions, including training are key to mission success.

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