Overview of the Mobile Servicing System for the International Space Station

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ABSTRACT

The Mobile Servicing System (MSS) will play a critical role in the on-orbit assembly, external maintenance and operations of the International Space Station. This paper reviews the mission and tasks to be performed by the MSS on the Station and provides and overview of the design of the MSS. Several examples illustrate how the mission requirements have shaped the design features of the MSS.

1. INTRODUCTION

The launch of the first module, "Zarya", of the International Space Station (ISS) in November 1998 marks the beginning of a period of unprecedented on-orbit construction to establish a permanent outpost for mankind in space. The Space Station as shown in Fig. 1 after completion of assembly will constitute a unique laboratory for research in material science, life sciences and other areas of scientific research.

Robotic systems provided by Canada will play a key role during the assembly of the Space Station in orbit and for the external maintenance of the station. This paper discusses the major mission requirements and corresponding design solution for the Mobile Servicing System (MSS) on the Space Station

2. MISSION AND ELEMENTS OF THE MOBILE SERVICING SYSTEM

2.1 Mission of the MSS

The MSS is being designed to perform the following functions on the Space Station [1]:

- Space Station Assembly including removal of Space Station elements and equipment from the shuttle cargo bay.
- Space Station external maintenance including changeout of Orbit Replaceable Units (ORU), actuation of mechanisms, mating/demating utilities, and visual inspection.
- Transportation on the Space Station of payloads such as Space Station elements, attached payloads and ORUs.
- Servicing of Space Station external payloads including ORU changeout, harvesting and replenishment, visual inspection, temporary provision of power, video and data connectivity, and visual inspection.
- Deployment and retrieval of free flyers by capturing and maneuvering to appropriate sites on the Space Station or deploying from the Station.
- EVA support including transporting or positioning of EVA crew, providing temporary storage, viewing, lighting.

2.2 Elements and Configuration of the MSS

The diversity of the tasks to be performed and the need to reach worksites all over the Space Station drive the design of the MSS towards a mobile system with multiple manipulators as shown in Figure 2. The large Space Station Remote Manipulator System (SSRMS) is designed to perform the capture, manipulation and berthing operations for large payloads. MSS functions requiring dexterous capabilities are satisfied by the smaller, dual-arm Special Purpose Dexterous Manipulator (SPDM).

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The SSRMS, an operations platform called the MSC Base System (MBS), and a Mobile Transporter (MT) together form the Mobile Servicing Centre (MSC). The MT provided by the United States is designed to move along rails on the Space Station truss to transport the MBS, SSRMS, SPDM and other payloads. The SSRMS and SPDM feature standardized "LEE/PDGF" interfaces dicussed below which allow the MSS to be configured in a number of different ways. The SSRMS and SPDM can "work together" as shown in Figure 2, or can attach themselves separately to the MBS or fixed points on the Station modules as required for different tasks.

The elements of the MSS are connected through a common computer and video network, and are controlled from one of two Robotic Work Stations (RWS) in the pressurized environment of the Station nodes. The MSS electronics equipment located outside the MSC and SPDM forms the MSS Control Equipment (MCE).

3. OPERATIONAL REQUIREMENTS AND DESIGN FEATURES OF ROBOTIC ELEMENTS

3.1 Space Station Remote Manipulator System

The SSRMS shown in Figure 3 is a 7-joint symmetrical manipulator approximately 17 metres in length when fully extended. A symmetrical arrangement of joints and a Latching End-Effector (LEE) at each end allows either end to attach to payloads, or to serve as a base for the SSRMS, providing that an appropriate Power Data Grapple Fixture (PDGF) interface is available. This design feature allows the SSRMS to "walk" on PDGFs and leave the MBS to use PDGFs on various Space Station modules as an operating base. This capability of peripedition greatly increases the reach of the SSRMS on the Station as required during the assembly of the Station, e.g. as shown in Figure 5.

The LEE along with the PDGF interface are shown in Figure 4. The LEE incorporates a snare mechanism, a rigidizing carriage mechanism, a latching system and umbilical connection. The snare mechanism is designed to snare the protruding probe of the grapple fixture. After the snare is closed, the carriage containing the snare mechanism and the snared probe is drawn into the LEE until the grapple fixture base plate is in full contact with the face of the LEE with a specified preload. If a higher stiffness interface is required e.g. when serving as the operating base of the SSRMS, or if power, data and video is to be transferred across the interface, a latching mechanism is activated, and an umbilical connector is engaged with its mating connector on the Grapple fixture. Power, data and video may be passed through the SSRMS to operate the SPDM while attached to the SSRMS LEE or to support the keep-alive power, telemetry and command requirements of payloads attached to the LEE. Each SSRMS LEE also incorporates a six-axis force-moment sensor which enables a force-moment control capability (FMA) of the SSRMS. Four video cameras are mounted on the SSRMS, one fixed camera at each end effector, and one, along with a pan and tilt unit on either side of the elbow joint on the main booms. A light is provided with each of the cameras.

The 7 joints of the SSRMS are arranged in clusters of three joints near each end of the manipulator to act as a "wrist" and "shoulder" respectively, with an additional joint at the midpoint "elbow" position. Starting from either end, the joint sequence is roll, yaw, pitch, pitch, pitch, yaw, roll. All joints are identical and have a range of travel of +/-270 degrees. Because the number of joints exceeds the 6 degrees-of-freedom in which the manipulator tip is being controlled, the manipulator is classified as kinematically redundant. The kinematic redundancy increases the operational flexibility by allowing to control the motion of the "elbow" independently of the payload motion motion in order to assist maneouvering the SSRMS around station hardware and helping to avoid kinematically singular configurations.

Operations using the SSRMS involve the handling and positioning of a wide range of payload shapes and mass properties. The mass range of payloads which can be handled by the SSRMS is from zero (i.e., no payload) up to 116,000 Kg, which is representative of a fully loaded shuttle orbiter. Assembly operations typically require the positioning of large payloads relative to berthing interfaces with an accuracy in the order of 5 to 10 cm. A "Space Vision System" (SVS) supports the precise positioning of payloads with the SSRMS in the absence of suitable direct vision/video reference from the berthing site. Figure 6 shows a typical module berthing scenario as seen from an SSRMS elbow camera. From such a video image, the SVS computes the relative position of the module berthing interfaces by photogrammetric analyses of the location of "SVS Targets" on the modules. The criticality of the Space Station assembly operations and the need to reach into the Cargo Bay of the Space Shuttle drive the video, power and control systems of the SSRMS to full redundancy in order to satisfy the requirement to "fail operational" with full performance capability. In addition, the SSRMS design is "scarred" for a third "back-up" command string which would allow limited SSRMS operations after the occurrence of failures both in the primary and secondary string.

3.2 Special Purpose Dexterous Manipulator

The SPDM is shown in Figure 7. The robot is made up of a body and two manipulator arms attached to shoulder structures on the "upper" body. The upper body has a PDGF compatible with the SSRMS LEE and the "lower" body has a LEE. Both interfaces provide full power, video and data connectivity to the robot. Thus the SPDM can operate either while attached to the SSRMS, or when attached to a PDGF on the MBS, where it is also stored while not in use. The lower body features two outriggers carrying cameras and lights on pan/tilt units (CLPTA) and a tool holder with 4 tools for special operations. The SPDM lower body also provides a platform for the temporary attachment of an ORU carrier for several ORUs. A roll joint in the body allows the upper body including the arms to rotate relative to the LEE, cameras and tools.

The two SPDM arms are identical 7-joint manipulators with a straight-arm reach of about 3.3 m and a payload capacity of 600 kg. The arms have a clusters of 3 joints at the shoulder and near the tip, with a pitch joint at the elbow position near the midpoint of each arm. The arms have the same joint sequence as the SSRMS and are therefore described by similar kinematic equations. The tip of each arm is equipped with an ORU-Tool Changeout Mechanism (OTCM) and the wrist of each arm contains a six axis force-moment sensor. The OTCM incorporates a parallel jaw gripper compatible with standard H and micro fixtures, an extendable 7/16 inch socket drive, a camera with a two stop zoom lens and two lights, and an extendable umbilical mechanism. The umbilical can provide power, data and video connectivity to SPDM payloads.

The SPDM is employed for numerous dexterous operations in assembly and maintenance such as handling and replacing ORUs, connecting/disconnecting utilities, attaching covers, actuating mechanisms with the socket drive, and performing operations with special tools. Figure 8 shows examples of dexterous tasks on the Space Station which require that the robot follows a constrained motion ("hinged motion"). The SPDM can also act as an extension of the SSRMS by means of the LEE on its lower body. About 250 ORUs of various designs are designated for robotic servicing on the Space Station. The dexterity of the tasks require a resolution of motion of the SPDM arms of 2 mm, and a high-performance programmable force-moment control capability (FMA) to avoid the possibility of jamming ORUs in their alignment guides.

Most operations are performed while the SPDM is attached via its PDGF interface to the SSRMS which positions the SPDM at the worksite. While performing ORU extraction or insertion with one arm, the SPDM is usually stabilized by attaching the OTCM of the other arm to a stabilization "H-fixture" near the worksite as shown in Figure 9. Once a failed ORU has been removed from its receptacle on the Station, the second arm removes the replacement ORU from the ORU carrier in order to free up a storage location for the failed unit. After the first arm has stored the failed ORU on the carrier, it is now used to stabilize the SPDM while the replacement ORU is installed on the Station by the second arm. The "Single ORU Storage Location" logistics concept for Space Station ORUs drives requirements for the SPDM Body Joint as well as for the dual-arm configuration of the SPDM.

The operations performed by the SPDM are of lower criticality to the Station in comparison to SSRMS operations since Extra-Vehicular Activity (EVA) by astronauts can be regarded a "second string" for performing maintenance on the Station. Safety requirements dictate that the SPDM fail "safe" which implies that after the occurrence of a failure the SPDM has to attain a state which is safe with respect to the SPDM element, its payload, and the Space Station. This usually requires that the SPDM has the capability to extract itself from the worksite. To this end redundancy is required for a number of functions of the SPDM such as payload release and bolt torquing.

3.3 Robotics Workstation

The MSS manipulators are controlled from one or two dedicated Robotic Work Stations (RWS) in the pressurized, shirt-sleeve Space Station environment, one in the US Laboratory Module and one in the Cuplola as shown in Figure 10. The control station-to-operator interface includes a number of displays for video views of operations, a command and control display providing graphical and numerical information and soft keys activated by a pointing device, two hand controllers for manual manipulator commands, and a keyboard. The man-machine interface concept with two hand controllers to "fly" the manipulators using rate commands arose from a comprehensive trade-off study among 6 competing concepts conducted in the early 1990s, involving astronauts from different countries. This fairly conventional concept is also employed on the Space Shuttle and hence maximizes commonality between Shuttle and Station for Space Station assembly operations.

Concepts for an additional control station located in the Space Station Control Center on the ground are discussed in [3]. This control station represents a future enhancement of the MSS to provide the optional capability to operate the MSS from the ground. This control station would provide a similar operator interface as the on-orbit workstation, but would include some additional features to accommodate communications delays and other problems associated with remote operation.

3.4 Control Modes and Features

The control modes for the SSRMS and the SPDM are quite similar and include Human-in-the-Loop control modes and Automatic control modes [4]. Human-in-the-Loop control modes are generally tele-operator modes where the operator controls the manipulator Point-of-Resolution (POR) with the aid of resolved motion control algorithms in the manipulator control software (Manual Augmented Mode), or on a joint-by-joint basis (Single Joint Mode). In the Automatic modes, the operator takes on more of a monitoring role, initiating, observing, and perhaps modifying automated operations. Resolved motion or joint-by-joint operation is also available in the Automatic modes.

A number of control features may be selected by an operator to enhance manipulation capabilities and reduce operator workload. Some of the most important control features are:

- *Force-Moment Accommodation (FMA)*: Provides active backdriving/compliance to external forces and moments measured by force-moment sensors at the manipulator tip.

- *Position/Orientation Hold Selection (POHS)*: Automatically controls errors on uncommanded degrees-of-freedom of the manipulator in Manual Augmented mode.

- *Arm Pitch Plane Change (APPC)*: The kinematic redundancy of the manipulator is used to rotate the plane of the arm defined by the three pitch joints while the tip of the manipulator is held stationary. This allows repositioning of the arm to avoid collisions or provide better viewing or to avoid joint limits.

3.5 Space Vision System

An important operational component of the MCE is the Artificial Vision Unit (AVU) implementing the Space Vision System functionality discussed earlier. The AVU provides manipulator payload positioning data to the MSS operator in the form of graphical and textual displays. The AVU is capable of utilizing the output of any of the MSS or Space Station cameras for photogrammatic image processing in real-time at the video-frame rate of 30 Hz. The AVU development builds on the Space Vision System technology tested during Shuttle mission STS-52 [5].

4. SUMMARY AND CONCLUSIONS

The MSS will play a critical role in the assembly, maintenance and operation of the International Space Station. The robotic tasks on the Station are quite diverse and require a mobile robotic system with multiple manipulators in order to be able to perform the required robotic functions at various worksites across the station. The larger SSRMS manipulator is primarily used for the handling of large payloads while the SPDM, in conjunction with the SSRMS, is designed to perform dexterous maintenance operations involving smaller ORUs.

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LIST OF ACRONYMS

AVF	Artificial Vision Function
AVU	Artificial Vision Unit
EVA	Extra-Vehicular Activity
FMA	Force-Moment Accommodation
FMS	Force-Moment Sensor
HCA	Hand Controller Assembly
LEE	Latching End Effector
MBS	MRS Base System
MCE	MSS Control Equipment
MRS	Mobile Remote Servicer
MSC	Mobile Servicing Centre
MSS	Mobile Servicing System
MT	Mobile Transporter
ORU	Orbit Replaceable Unit
OTCM	ORU/Tool Changeout Unit
PDGF	Power Data Grapple Fixture
POR	Point-of-Resolution
RWS	Robotic Work Station
SPDM	Special Purpose Dexterous Manipulator
SSRMS	Space Station Remote Manipulator System

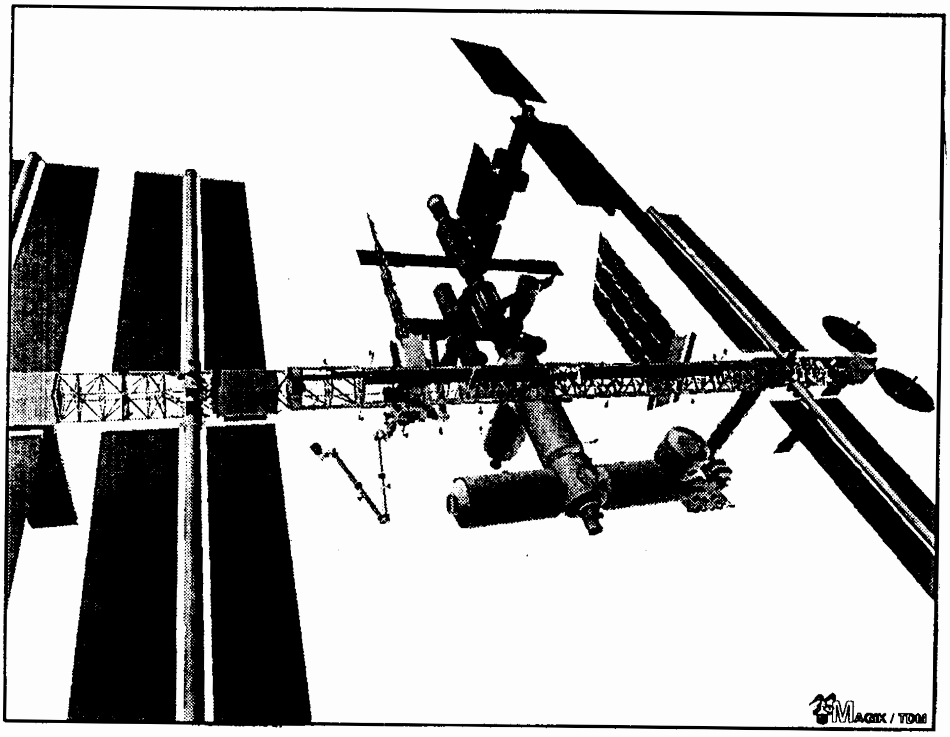

Figure 1: International Space Station

Figure 2: Mobile Servicing System