SPECIAL PURPOSE DEXTEROUS MANIPULATOR (SPDM) REQUIREMENTS VERIFICATION

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Abstract

The Special Purpose Dexterous Manipulator (SPDM) is the first space robot to be designed based on a large number of commonality and legacy components. Therefore the the designers of the SPDM could not utilize the conventional approaches to the Verification Planning and Implementation of this complex system. This paper describes the approach taken by the SPDM designers and Customer in addressing this issue.

Introduction

The Special Purpose Dexterous Manipulator (SPDM) is the latest Space Robot being developed by McDonald Detwiller Space and Applied Robotics (MD Robotics, previously Spar Aerospace) for the Canadian Space Agency as part of the Canadian contribution to the International Space Station Program – the Mobile Servicing System (MSS). The SPDM is a dual-arm robot that responds to the ISS requirement for an external Dexterous Robotic alternative to Extra-Vehicular Activity. It is a complementary and integrated component of the MSS.

The design and development of the SPDM presents several challenges related to the nature of the Fixed Price program undertaken by MD Robotics Ltd.

A number of drivers affect the SPDM Verification Process:

(1) The SPDM initial design was started and attained various levels of maturity for various components (PDR and CDR for some items) under the Space Station Freedom environment, then the Program was stopped and finally restarted under the harsher environment in which the International Space Station is being built,
(2) The SPDM is the first space robot to utilize previously developed and space certified robotic components, such as Space Station Robotic Manipulator System (SSRMS) Orbital Replaceable Units (ORU) and components,
(3) Most of the electronics are based on previous designs developed for the SSRMS, with various degrees of modifications and component changes, and
(4) Similarly, the SPDM S/W is composed of commonality (SSRMS) Software CSCIs, legacy (high percentage of commonality with previous designs) CSCIs and new Software.

MD Robotics has defined and is employing a unique, tailored Verification Program for the SPDM Systems and Components, including:

(1) New Verification Planning and Tracking tools
(2) An Incremental Buyoff process has been defined to facilitate full Customer visibility into the progress made during the verification process
(3) Early testing of software components integrated in the overall SPDM Control model
(4) The use of Flight Hardware for early software-to-hardware integration, will be described.

A brief description of the facilities created in support of the SPDM Verification effort will be provided, with emphasis on the common Test Host equipment developed to support both these environments.

The Special Purpose Dexterous Manipulator (SPDM)

The SPDM Purpose and Architecture

The Special Purpose Dexterous Manipulator (SPDM) is the latest Space Robot being developed by McDonald Detwiller Space and Applied Robotics (MD Robotics, previously Spar Aerospace) for the Canadian Space Agency as part of the Canadian contribution to the International Space Station Program – the Mobile Servicing System (MSS). The main elements of the MSS

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are the SSRMS, the MBS, and the SPDM. The SSRMS, a seven-degree of freedom Robotic Arm, will be used for assembly maintenance servicing of the International Space Station and Transportation of its external payloads. The MBS forms the base for SSRMS and SPDM operations and will be transported along the Space Station truss to the work site by the Mobile Transporter. The SPDM is a dual-arm robot that responds to the ISS requirement for an external Dexterous Robotic alternative to Extra-Vehicular Activity. It is a complementary and integrated component of the MSS.

The SPDM is to be controlled by astronauts within the ISS using the MSS Control Equipment (MCE). The MCE is a set of specialized hardware and software which functions with the Space Station distributed systems to provide the capability to operate the MSS components. The MCE is comprised of the Robotic Work Station itself, the resident MSS Operations Control Software, the Artificial Vision Unit and the Graphical User Interface software which runs on the Space Station Portable Computer System.

The primary mission of the SPDM is the reduction of EVA hours by robotic execution of Space Station external maintenance tasks. These tasks consist of the change out and or replacement of failed externally mounted Orbit Replaceable Units (ORU). More than 200 ORUs at various locations on the Station will be "roboticaly compatible" and are hence designed for robotic removal and replacement by the SPDM. These ORUs vary considerably in size and configuration, including the design of their mounting alignment systems and of the visual targets provided. A typical ORU exchange scenario involves operation of the SPDM at the outer end of the SSRMS by an astronaut located within the Space Station. The SSRMS provides power, data and video connectivity to the SPDM in addition to performing large scale positioning to enable the SPDM to reach the work site.

The SPDM consists of a main body and ORUs and will be launched as nine (9) separate components mounted on special Flight Support Equipment (FSE) integrated to a Space Lab Pallet. NASA astronauts will perform the SPDM on-orbit assembly and deployment during a nominal 6 hour EVA.

In the event of failure, the SPDM design permits faults to be isolated to individual ORUs. Faulty SPDM ORUs will be replaced on-orbit via EVA with IVA and Flight Controller support. SPDM ORUs will be available on the ground for delivery to orbit when required.

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The SPDM History

The last of the three Robotic Components of the Canadian Space Station Program, the SPDM has been developed in the shadow of the Space Station Remote Manipulator System (the Canadarm's bigger, newer cousin), and the Mobile Base System. Station redesign and delays, and budgetary constraints driven by the work on the first two Robotic Components drove the Canadian Space Agency to stop work on the SPDM in the summer of 1995. The Project was shut down for a period of 20 months. At the time of shutdown, the overall system had attained PDR level of maturity and the various components had reached different developmental milestones, such as PDR or CDR.

The need for an SPDM-like robot to ensure assembly and maintenance of the Space Station has not disappeared, however, so the CSA renegotiated the Project with MD Robotics on a Firm Fixed Price basis, and re-started the SPDM development in August 1997.

Impacts on SPDM Verification Planning

The SPDM Verification Plan had to accommodate a mix of components at various levels of maturity, with each type of component requiring a slightly different verification approach:

a) Commonality Components - Components developed, tested and Certified for flight under the MSSP Program and reused as off-the-shelf items for the SPDM. SPDM Items common with the MSS were fully Qualified and Certified under earlier phases of the Canadian Space Station Program.

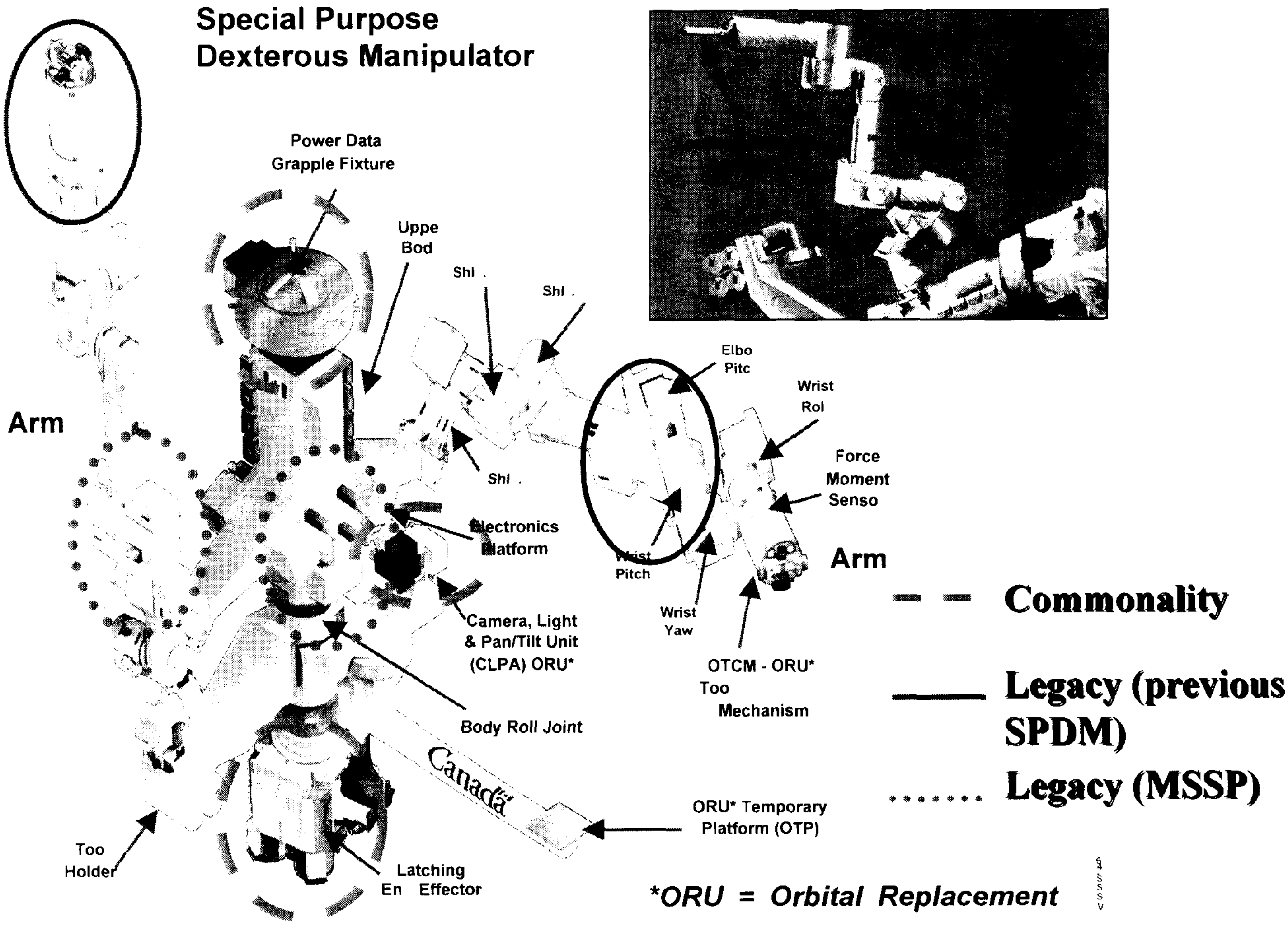

Figure 1 – The SPDM Architecture

The SPDM Program will compare by analysis the original (MSS) Certification Environment of such items and the environment that the Item will be exposed to when used in the SPDM. The Program must ensure that the SPDM environment is equal to or less severe than the one for which the MSS Item has been certified or, if the latter cannot be achieved, MD Robotics will perform re-qualification as required. This Analysis will be the only Verification Document addressing Commonality Equipment, and will be submitted in support of the Certification request for the SPDM Element. No separate Certification will be requested for the MSS Commonality equipment used on SPDM if the Analysis shows they are useable as-is.

The Verification activities for such Items consist of the Flight Item manufacturing inspection and in-process tests, and complete Acceptance Test. These Verification activities will be performed using the MSS Program test requirements and documentation.

b) Legacy Components - Items that were developed to CDR level under previous MSS Contracts. These Items are assumed to have successfully completed their Design Verification Phase, but the SPDM Program must confirm this. The SPDM Program will be responsible for the overall Verification Completion for the Item, and will have to complete any outstanding Design Phase Verification activities that might be found during the attempt to close the Design phase verification

MD Robotics is responsible to compare every Commonality Item's original design Environment and Requirements and the one the Item will be used in on the SPDM, and to ensure that the SPDM environment is equal to or less severe than the one for which the Item has been originally designed. The

SPDM Program is also responsible for any re-verification and re-certification of the design if any major redesign of the item is required.

c) New Components - New designs, to be developed for the SPDM under the present Contract will undergo a full-fledged Verification Program based on Protoflight and Qualification Testing.

The SPDM Verification Planning and Tracking Tool

The Unit Specifications for the SPDM reflect its legacy. Some are 10 or more years old, created for a totally different system, with features not used on the SPDM, and therefore in most cases could not fully trace to the SPDM System Specification requirements. Others are 4-6 year old, created under the previous incarnation of the SPDM program, and some are new. The MD Robotics designers decided against re-writing all these Specification for the SPDM.

Most off-the-shelf Verification planning tools surveyed were deemed to be too cumbersome for use on the SPDM, requiring reloading of old Specifications and of full (old) Verification Matrices and would complete traceability of these disjointedly created Specifications just to be able to start the planning effort. In order to minimize the effort, the MD Robotics Systems Team developed it's own tools in an MS Access Database, the Verification Allocation Database (VAD).

The VAD is different in it's approach to traceability and mandatory roll-up of Verification. All the SPDM Specifications produced (new, legacy and commonality) were loaded into the VAD, but traceability has been established only against the functional requirements of the SPDM System Specification, tracing them down to the lowest unit where they are actually implemented and verified. Derived "support requirements" (which complete the Unit Specifications at lower level) are not traced, nor is their Verification "rolled up" to the System level for Certification purposes. This allowed MD Robotics to trace only those requirements that are significant to the verification of the SPDM System, and to sidestep irrelevant "commonality" driven requirements from the older Specifications.

The VAD is used at all levels of the SPDM, with Subsystems or ORUs at each level of decomposition having their own VAD, and applying the same overall traceability approach below it. For the SPDM System Certification, the roll-up of Verification Completion activities is performed against the System Specification requirements, using the traceability feature of the database.

The VAD allocates the Verification activities for every requirement not just by method (Analysis, Test, Demo etc.), but also defines additional specifics for each method, such as types of analysis, facilities for test, organization or group responsible for performing the task, etc. These allocations are then considered when defining the task load for the various engineering groups working on the Program. The VAD collects the Verification Completion Documents (e.g. Test Reports) and automatically generates the various forma Verification Closure forms required by CSA for the SPDM System Certification.

Approach to SPDM Verification

A number of new approaches to integrated Verification and Risk mitigation, such as early testing of software components integrated in the overall SPDM Control model and the use of Flight Hardware for early software-to-hardware integration have been implemented on the SPDM.

Use of Flight Hardware for initial software testing and integration

The SPDM Contract requires the manufacture of 21 Joints (three arms including one spare), as well as a Flight Equivalent Engineering Model OTCM. In order to mitigate the risk of problems during software and hardware integration at the system level MD Robotics decided to use a Joint cluster (3 joints arranged as the arm's elbow or shoulder) and the EM OTCM as an early-integration software Test Bed. The Joints will undergo only a set of Functional Tests prior to their allocation to this Quick Test Bed, and will be fully tested after the software testing is completed, and will be used for the MD Robotics SPDM Arm.

Use of the SPDM Simulation Model as a software test bed

An SPDM Simulation Model has been built with the intent to allow not only Simulation Verification of the System, but also to act as an early test bed for software modules. The functionality of the main SPDM CSCI has been modeled in a manner that allows incrementally developed individual CSCs to be "dropped" into the model and run against the previous results of the model without the real code, thus acting as an initial test bed for the code. Ultimately the flight code will replace their respective modeled parts in the System Simulation, to create a very flight-like Simulation Model that can be used for training purposes in the future.

Environmental Testing

Since some of the major ORUs of the SPDM are tested as Protoflight components, it was extremely important to coordinate the "vertical" accumulation of environmental testing cycles up to the System level. This was accomplished in the early planning of the Verification approach and submitted to Customer (CSA) approval as part of the Program baselining.

Neutral Buoyancy and EVR Tool Testing

A full Neutral Buoyancy test was performed early on into the program at the NASA NBL facility (Figure 2), to ensure that astronauts can deploy and maintain the SPDM. The comments and inputs received from this test were incorporated into the baseline design.

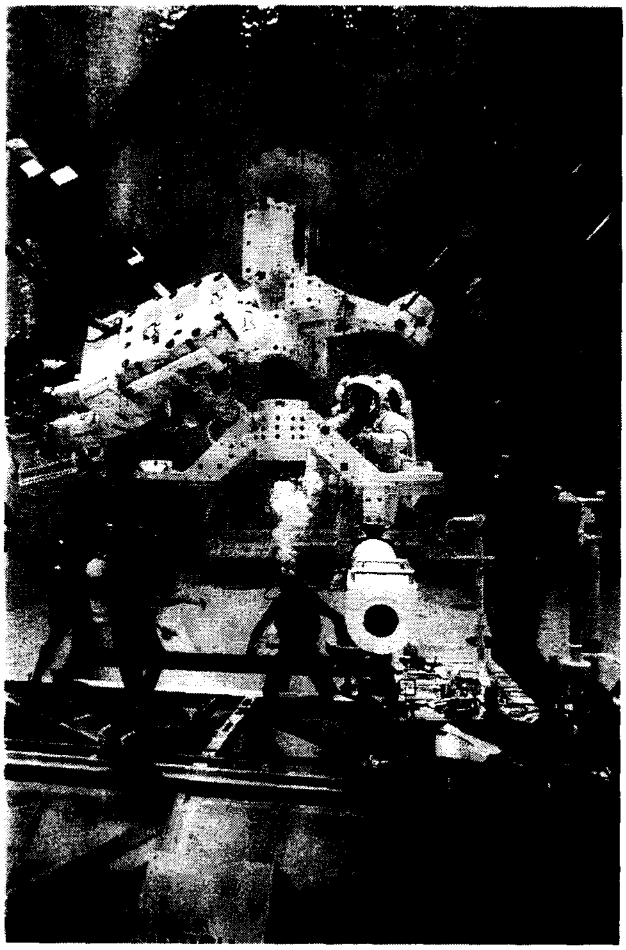

Figure 2 – The SPDM Neutral Buoyancy Lab (NBL) tests

Since the NBL test does not cover SPDM utilization, additional tests were performed with the SPDM Socket Extension Tool (SET) and with the SPDM Ground Testbed (GT). The SET compliance tests (Figure 3) concentrated on the ability of the SET to be used at marginal angles of approach to bare bolts, while the GT tests (Figure 4) are demonstrating the ability of the SPDM to operate the OTCM alone and with the SET.

Figure 3 – The Socket Extension Tool (SET) tests

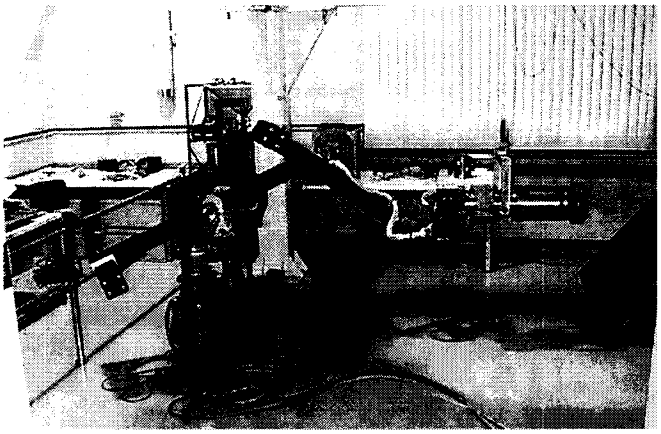

Figure 4 -- The SPDM GT test setup

SPDM Verification Facilities

The SPDM Program will use some the test beds and equipment previously developed for the MSSP, but some critical System level facilities will not be available to it due to the ongoing test activities on the other Program. Therefore it was decided that a new set of test beds would be developed:

a) The SPDM Avionics Integration Facility (SAIF) – allowing multi-user testing of CSCIs during the development stage, as well as CSCI integration with it's hardware platform and testing of the SPDM avionics at increased levels of integration up to and including End-to-end integration with Space Station Control software components

b) The SPDM Integration Test Facility (SITF) – allowing integration and testing of the SPDM Flight Hardware as well as SPDM hardware with Space Station hardware (the Robotic Work Station, from which the SPDM will be controlled on-orbit by the Astronauts). The SITF allows offloading of the arm weight by counter balance weights (Figure 5).

These two test beds share a common design for the Test Equipment Host, allowing the same test control software and equipment to run tests both on the software and the hardware test beds. The benefits of this approach are much lower development and maintenance costs, test script re-use, easier test equipment troubleshooting, capability to use one test crew on all System levels tests, etc.

The Incremental Verification Process

The SPDM is a Fixed Price Program, normally allowing both sides, if they wanted, to minimize the Customer's

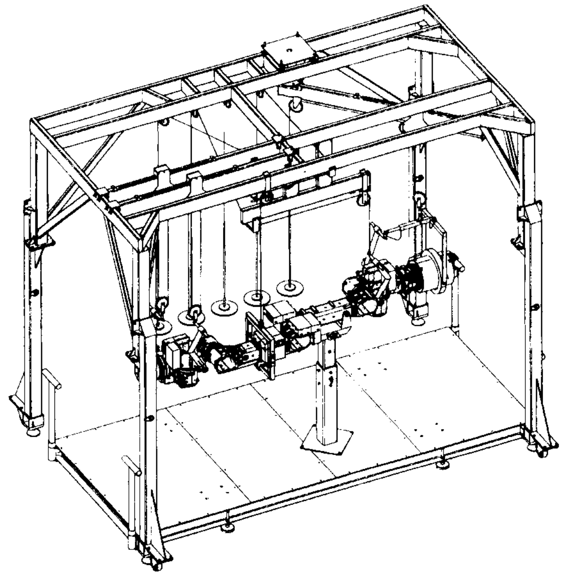

Figure 5 – The SPDM SITF test setup

involvement in the Verification completion and buy-off until the Acceptance Review. Since this could create unnecessary risk to the Program, the CSA and MD Robotics have agreed upon an Incremental Verification approach coupled with clear rules for re-verification and re-certification of components or the SPDM System.

In order to obtain the System Certification and Acceptance, MD Robotics must show that each requirement in the System Specification has been fully verified at all the levels to which it is applicable. The VAD accumulates the various documents containing these "proofs of verification" and automatically "rolls them up" to the System level to provide the Customer required data. The CSA is being provided with and approves Verification Status Reports at critical Program Milestones. For example at the SPDM CDR all of the stand-alone Design Verification tasks, such as Analysis, were reviewed and closed as completed, baring any unforeseen events that might require re-verification in the future (e.g. due to redesign driven by failures in test).

Conclusion

The SPDM Program has poses some interesting Verification challenges to both the Canadian Space Agency and to its Prime Contractor, MD Robotics, driven by the mixture of old and new components. Careful planning and good interaction between the CSA and MD Robotics teams has resulted in a viable approach to the SPDM System verification, one that ensures good verification coverage and early risk mitigation with a minimum of overhead and unnecessary cost.