Lessons for Future In-Space Telerobotic Servicing from Robotic Refueling Mission

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Abstract—**The Robotic Refueling Mission (RRM) was a multi-phased technology development effort by the National Aeronautics & Space Administration (NASA) and the Canadian Space Agency (CSA). The program leveraged the existing robotic systems and expertise of the International Space Station (ISS) program and the tool design and satellite servicing expertise of NASA's Exploration & In-space Services (NExIS) Projects Division at Goddard Space Flight Center (GSFC) to evaluate new hardware and techniques for on-orbit telerobotic servicing. Between 2011 and 2021, two external ISS payloads housed over a dozen robotic tools and adapters designed to service a variety of existing and novel satellite interfaces. Robot operators at NASA's Johnson Space Center (JSC) and CSA used the Special Purpose Dexterous Manipulator (SPDM) to retrieve and operate these tools for tasks such as cutting wires or multi-layer insulation blanketing, removing valve caps, mating electrical connectors, transferring fluids, and performing visual inspections inside a vehicle. Each phase of RRM involved years of preparation. Tool and interface designs were prototyped and evaluated using both NASA and Canadian ground robotic systems. Procedures were developed by GSFC engineers and vetted in partnership with JSC and CSA robot operators. GSFC engineers were trained to provide real-time support during on-orbit operations. These preparatory efforts and the successful on-orbit evaluations yielded an array of lessons for future in-space telerobotic missions. Designing robotic tools for the space environment requires special consideration of materials, indicators, and differences between ground and flight use cases and environments. When there is a limited window for on-orbit operations, devoting time and high-fidelity hardware to ground testing can be critical. Needs during potential troubleshooting are more essential to camera view quality, frame rate, and position requirements more than nominal operations. Detailed hardware manuals, nominal and contingency procedures, along with clearly defined operations team roles and protocols are vital for efficiency. RRM also demonstrated how the ISS can be utilized to increase the technology readiness levels required for future missions and led to additional technology partnerships between NExIS and the ISS program. The lessons from RRM are currently being applied to designs, operations concepts, and ground test methodology for missions such as On-orbit Servicing, Assembly, and Manufacturing 1 (OSAM-1) and Mars Sample Return.**

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1. INTRODUCTION

The International Space Station (ISS) and its robotic systems provide an invaluable resource to mature technologies necessary for future on-orbit servicing, assembly, and manufacturing missions. The Robotic Refueling Mission (RRM), a joint effort between the National Aeronautics and Space Agency (NASA) and the Canadian Space Agency (CSA), utilized this resource to identify and develop the tools, techniques, and procedures necessary for refueling and servicing a satellite not originally designed to be serviced in orbit. Through multiple phases spanning eleven years, RRM focused on demonstrating the steps required to refuel a legacy spacecraft with storable propellants and the steps required to replenish cryogens. These included cutting lock wires, manipulating fasteners and thermal blankets, removing caps, connecting to and resealing a fuel port, transfer of fluids in zero-g, and long-term storage of cryogenic fluids. Through design, construction, ground testing, and successful completion of all on-orbit operations, many lessons were learned for future telerobotic servicing missions.

2. Space Station Robotics & Payloads

Mobile Servicing System

The Mobile Servicing System (MSS) is a complex system of robotic hardware essential for ISS construction, maintenance, and resupply. At its core is the Space Station Remote Manipulator System (SSRMS), a 57 ft. long, 7 Degree of Freedom (DOF) robotic arm [1]. The arm is identical about its elbow; either end can be the shoulder or the wrist with an end effector. It can be based on one of the ISS modules or on the Mobile Base System (MBS), which can travel along the length of the space station's truss on the Mobile Transporter (MT). The SSRMS is capable of maneuvering large payloads, such as visiting cargo spacecraft or ISS modules, or other robotic systems, such as the Special Purpose Dexterous Manipulator (SPDM). SPDM has two 11.4 ft. long [1], 7 DOF robotic arms and can manipulate smaller payloads or interfaces, including the RRM payloads and tools. The MSS is operated by flight controllers at Johnson Space Center (JSC) in Houston, TX and at CSA in Saint-Hubert, QC.

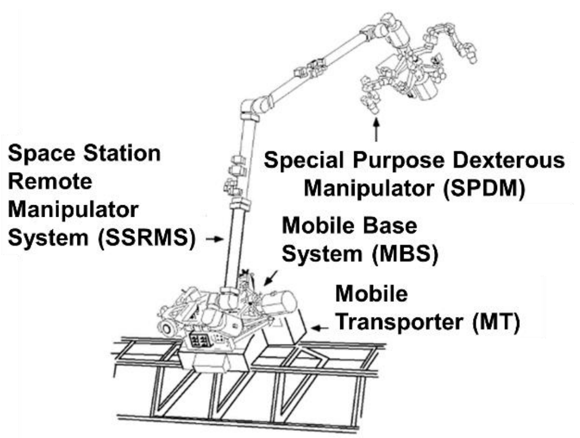

Figure 1. ISS Robotic Hardware, Adapted from [2]

External Space Station Payloads

The ISS provides an infrastructure for externally attaching equipment or experiments via four EXpedite the PRocessing of Experiments to Space Station (EXPRESS) Logistics Carriers (ELCs). These platforms are mounted to the ISS's truss; each provides multiple mounting points, as well as power and data to connected payloads. Two ELCs supported RRM operations: ELC4 on the starboard-nadir side for RRM Phases 1 and 2, and ELC1 on the port-nadir side for RRM3.

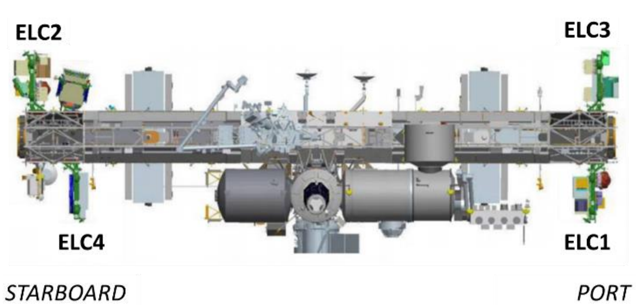

Figure 2. ELC Payload Sites on the ISS, Adapted from [3]

3. Mission Overview

The first phase of RRM focused on the steps necessary to refuel a legacy spacecraft and the early steps required for replenishing cryogens. Phase 2 focused on intermediate steps for cryogen transfer, and RRM3 focused on the final steps for cryogen transfer.

RRM Phase 1

The original RRM hardware was launched to the ISS on the final Space Shuttle mission, STS-135, in July 2011. The 550 lb., 33 in. x 43 in. x 55 in. module, which was the last payload to be removed from a Shuttle cargo bay during a spacewalk, was installed on ELC4 using SPDM in September 2011 [4]. It contained 4 tools to be used with the payload's various built-in interfaces; accommodations for modular taskboards, some of which included common satellite interfaces for evaluating the use of machine vision in orbital lighting conditions; and 1.7 liters of ethanol to demonstrate on-orbit fluid transfer. Ethanol was utilized instead of a traditional propellant to minimize risk to the station and its crew.

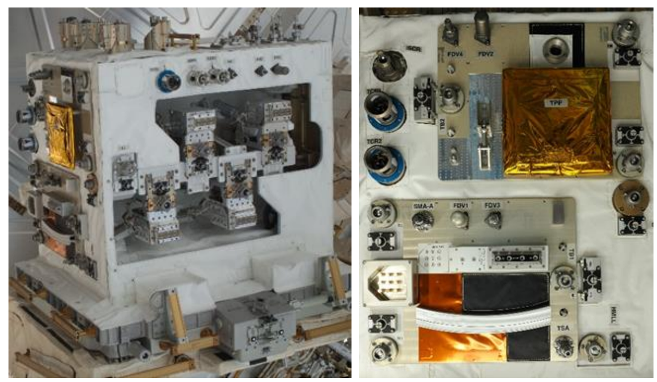

Figure 3. RRM Payload (Left) and Taskboards 1 & 2 (Right)

Each RRM tool consisted of an interface compatible with SPDM's end effector, mounting hardware and electronics for two orthogonal tool cameras, as well as the mechanism specific to that tool.

- The Wire Cutter Tool (WCT) was used to cut lock wires between fill and drain valves (FDVs). It also possessed a small gripper that was used to grasp and manipulate thermal blanketing and a blade to cut the blanketing closeout tape.
- The Safety Cap Tool (SCT) was used to remove and stow a FDV safety cap and its seal.
- The EVR Nozzle Tool (ENT) was used to open, transfer fluid through, and close a fuel-valve.
- The Multi-Function Tool (MFT) provided an interface for several small adapters used to perform tasks such as removing fuel-valve caps or a gas 'plug.' Utilizing exchangeable adapters instead of a separate tool for each of these tasks demonstrated how mass and volume could be saved on future servicing missions.

Figure 4. RRM Phase 1 WCT (Left) and SCT (Right)

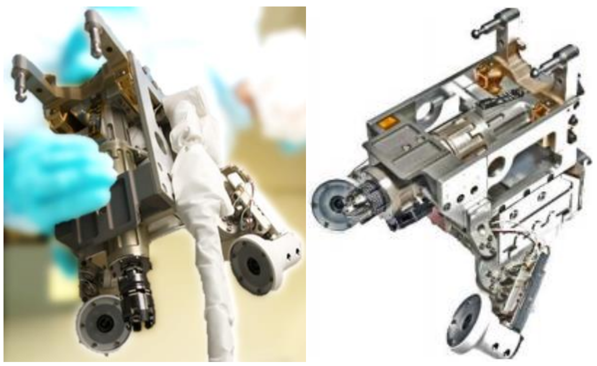

Figure 5. RRM Phase 1 ENT (Left) and MFT (Right)

RRM Phase 2

Two new taskboards and one new tool were launched to the ISS on the Japanese HTV-4 in August 2013 and the European ATV-5 in July 2014 [5]. Five new MFT-actuated adapters were included with the taskboards, which were installed on the RRM module by SPDM in April 2015 [6].

- The Electrical Plug Adapter (EPA) was used to robotically capture and remove a connector turnaround plug.
- The Wire Harness Adapter (WHA) was used to robotically mate an electrical plug followed by a connectivity check to verify the successful electrical mate.
- The Vent Plug Adapter (VPA) was robotically inserted into a vent line to demonstrate sealing a gaseous line prior to refueling.
- The Coolant Line Adapter (CLA) demonstrated how a coolant fitting could be robotically mated to an interface in preparation for the transfer of fluid through the valve; the adapter was connected to a tether on a spring reel to simulate typical hose forces (no coolant was transferred).
- The Blind Mate Adapter (BMA) was used to demonstrate robotic connection of an array of Sub-Miniature A (SMA) plugs in a receptacle box.
- The Visual Inspection Poseable Invertebrate Robot (VIPIR) tool possessed a flexible tube with a camera at its articulatable tip. This tube was extended and navigated through conduits of various materials to demonstrate performing inspections inside a spacecraft.

The taskboards also contained demonstration hardware for evaluating new solar cell technology, materials coatings, and machine vision fiducials [7], including the commonly available ARToolKit fiducial and a camera calibration pattern.

Figure 6. RRM Phase 2 Taskboard 3

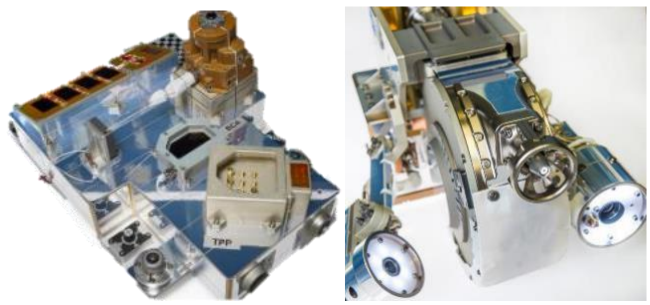

Figure 7. RRM Phase 2 Taskboard 4 (Left) and VIPIR2 (Right)

The RRM Phase 1 and 2 module, taskboards, tools, and adapters were removed from the ISS in March 2017. All hardware was disposed during the atmospheric re-entry of SpaceX CRS-10 except for the SCT and Taskboard 4, which were returned as pressurized cargo for analysis at GSFC.

RRM3

The 700 lb., 30 in. x 45 in. x 45 in. RRM3 Fluid Transfer Module (FTM), three new tools, and a mounting pedestal were launched on SpaceX CRS-16 in December 2018. Two of the tools, the MFT2 & VIPIR2, were second generation versions of hardware from previous RRM phases. The FTM also contained two new MFT2 adapters and demonstration hardware for cryogen transfer and thermal imaging. A broader suite of machine vision alignment fiducials, some of which are shown in Figure 8, and a larger calibration pattern for more flexible usage were also included. SPDM installed the FTM on ELC1 in December 2018 and installed the tool pedestal and tools in April 2019.

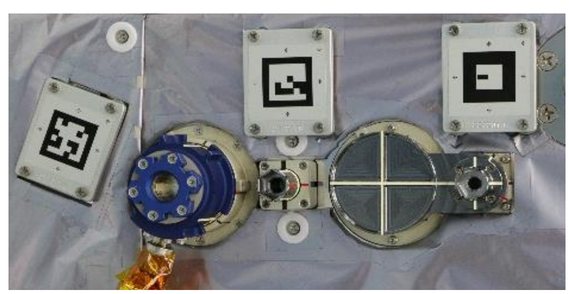

Figure 8. Examples of RRM3 Machine Vision Markers

- The Cryogen Servicing Tool (CST) was used to capture and feed a flexible, non-fixed cryogen hose into a receiver tank for fuel transfer.
- The VIPIR2 featured upgraded cameras and was the only RRM tool to use a wifi connection to transmit video instead of the data lines running through SPDM and the SSRMS.
- The MFT2 was the first and only RRM tool with adjustable Camera Positioning Mechanisms (CPMs), which allowed the tool cameras to be extended or pitched as needed for different tasks or adapters.
- The Cryogen Coupler Adapter (CCA) and Xenon Coupler Adapter (XCA) were intended to demonstrate fluid transfers via fixed, dedicated supply hoses.

Figure 9. RRM3 FTM (Left) and Tool Pedestal (Right)

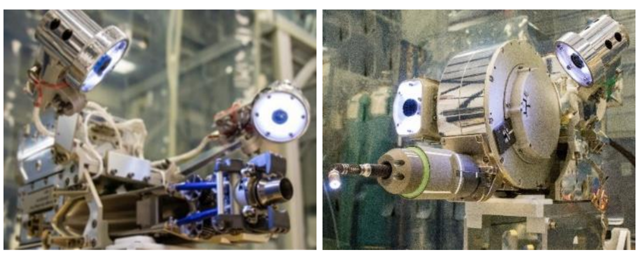

Figure 10. RRM3 CST (Left) and VIPIR2 (Right)

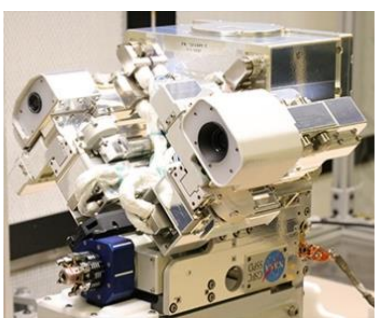

Figure 11. RRM3 MFT2

RRM3 demonstrated the first ever long-term storage of cryogenic fluid in space with zero boil off, although a cryocooler failure in April 2019 resulted in the stored liquid methane being vented prior to robotic testing. Most of the robotic tools were still maneuvered and operated as planned to gain valuable knowledge about the technology and techniques for transferring cryogens in space and robotically manipulating related interfaces. The FTM is scheduled to be de-orbited in 2022.

4. Robotic Development Activities & Operations

Preparation for on-orbit testing began long before the hardware was launched to the ISS. Each phase's goals were translated into preliminary hardware designs. For some tools and adapters, prototypes were tested using industrial robots in GSFC facilities to refine the design. Once either high fidelity CAD models or the physical hardware were available, the GSFC robot operators developed draft procedures with explicit details of how to maneuver and operate the tools. These procedures were evaluated using Macdonald Dettwiler & Associates (MDAs)'s Ground Trainer (GT) facility using robotic hardware and software representative of the systems onboard the ISS. Feedback from these testing events enabled the creation and refinement of procedures to be executed by JSC/CSA robot operators during on-orbit operations. Prior to on-orbit operations, contingency procedures were also documented and the GSFC operations team practiced supporting the robotic tasks and troubleshooting.

Procedure Development

Hardware testing was primarily conducted in GSFC's Servicing Technology Center (STC). A 6 DOF industrial robotic arm was used as a stand-in for one of SPDM's arms. MDA, who created SPDM's end-effector, provided an engineering model to GSFC to support hardware testing – the ORU Tool Changeout Mechanism Simulator (OTCM-S). This allowed prototype, engineering design unit (EDU), flight spare, and flight tools to be operated in a similar manner as they would be used in space and aided with nominal and contingency procedure development.

Robot operators at GSFC designed the robotic maneuvers and determined the OTCM commands necessary to perform the RRM tasks. These were documented in procedures, which robot operators at JSC and CSA translated for SSRMS and SPDM. To make this conversion as easy as possible, all maneuvers were relative to the previous location instead of listing specific Cartesian positions or joint angles.

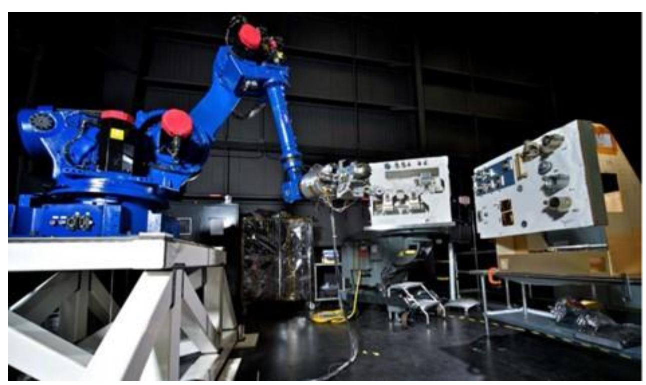

Figure 12. STC Configured for RRM Phase 1 Support

The robot control software used at GSFC includes a visualization component that displays the robot, tool drive, tools, and payloads. This visualization was upgraded for RRM3 to allow the user to view and control simulated cameras, including those on the robotic tool, and set the position and orientation of the tool tip and any attached adapter. This functionality enabled procedure development to begin before hardware was available for testing. Even when hardware was available, the visualization could be used to evaluate tasks with fewer required personnel and less risk. However, the simulation does not allow verification of contact forces, OTCM turns and torques, or motion of flexible hoses. An abbreviated period of hardware testing was still required to evaluate these items and complete the procedure drafts. For tasks that did not involve any of these factors, like machine vision testing, the visualization was the primary procedure development tool. Placement of machine vision fiducials and robot poses for camera calibration were determined using the software. The simulated camera views allowed the planning team to ensure the markers were visible and could be resolved by the machine vision algorithms.

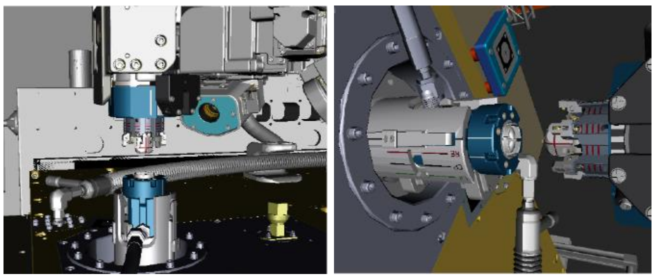

Figure 13. Simulated Payload (Left) and MFT2 Camera (Right) Views

The industrial robots utilized at GSFC allow effective evaluation of tool functionality and visual indicators, but do not fully replicate MSS dynamics and software features. MDA's GT facility includes a weight-offset version of one of SPDM's arms. The SPDM software at the GT and the on-orbit software can respond to external forces observed at the contact interface above a specified threshold. Human safety protocols also differed between the GSFC and GT facilities; since personnel are not permitted within the workspace of industrial robots at GSFC, GT testing provided the only opportunity to closely inspect and photograph the tools during robotic actuation. However, GSFC's industrial robots had a larger range of motion, while the GT robot's motion is restricted by its overhead suspension system. Neither facility could individually allow full evaluation of the task procedures; utilizing both was key to preparing for on-orbit operations.

Figure 14. RRM Phase 1 Tool Unstow Testing at MDA GT

At least one GT test campaign was conducted for each phase of RRM. Prior to testing, MDA engineers converted the GSFC procedures for the GT robot and software. This started the process of developing flight procedures; in some instances, the torques, forces, or step order from the GSFC procedures were not possible with SPDM. Working alongside the MDA engineers helped the GSFC engineers better understand the MSS system and prepare for on-orbit operations. At the end of each GT test campaign, the tasks were demonstrated for the flight controllers and other engineers from GSFC, JSC, and CSA who would be involved in on-orbit operations.

After GT testing, notes or changes to the procedures were evaluated once again at GSFC. The updated procedures were sent to JSC and CSA flight controllers, who combined them with other flight products from CSA to develop the flight procedures.

Operations Team

A team of 3 flight controllers – ROBO, Systems, and Task – at JSC and/or CSA commanded and monitored the MSS throughout RRM operations. ROBO led the team and was primarily responsible for communicating with other positions in Mission Control or at GSFC and decision-making when necessary. Systems was primarily responsible for commanding the system, monitoring the health of the MSS, and developing troubleshooting plans if required. Task was primarily responsible for guiding the execution of the procedures, monitoring the timeline, and maintaining awareness of the state of the ISS as a whole.

A team of approximately a dozen engineers supported RRM operations from GSFC. The Goddard Satellite Servicing Control Center (GSSCC) and STC received live video feeds and telemetry from the ISS to monitor the task and RRM hardware. The Ops Lead coordinated the team's activities and was the primary point of contact with the JSC and CSA team. Subject matter experts (SMEs) for specific pieces of hardware (e.g., cameras, hose management, pressurized systems, etc.) or tasks supported the Ops Lead. The robotics and tool SMEs staffed the STC; its robots and mockups were configured to assist with troubleshooting efforts as needed.

Figure 15. GSSCC during RRM On-Orbit Operations

Figure 16. STC during RRM On-Orbit Operations

Communication between the two teams took place over audio loops. The controllers at JSC and CSA used separate loops for intra-team conversations versus communicating with other personnel in Mission Control. There was also a dedicated loop for communication between the JSC and CSA team and the GSFC team. Technical discussions within the GSFC team took place on multiple discipline-specific loops. Personnel could only talk on one loop at a time but could listen to as many as they desired. Members of each team could communicate freely within their team, but ROBO and Ops Lead were the primary points of contact between the two teams. This was intended to prevent personnel, especially at JSC and CSA, from being distracted by discussions they did not need to be part of. Occasionally, for efficiency's sake, one of the GSFC SMEs would be invited to speak on the shared communication loop to provide the JSC and CSA team with necessary details or instructions.

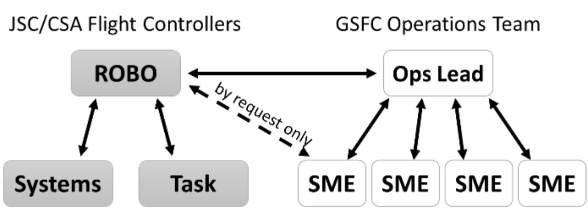

Figure 17. Communications Paths Between Teams During Operations

Operations Preparation

Shortly before operations, flight controllers and engineers from JSC and CSA participated in demonstrations at GSFC to familiarize themselves with the hardware, tasks, and contingencies. Development of contingency procedures was a joint effort; personnel from both teams needed to agree on what steps to take to ensure the flight system could perform them. In some instances, procedure steps were modified to reduce the likelihood or impact of a contingency. Flight procedures were reviewed by personnel at JSC, CSA, and GSFC prior to on-orbit operations.

Personnel at GSFC prepared for operations by conducting Operations Readiness Exercises (OREs). These ops simulations could take a variety of forms. The simplest involved just a few personnel verifying computer functionality, robotic hardware readiness, and communications and data links between the GSSCC and STC. The most complex involved the full GSFC operations team stepping through task procedures – with the ground robot standing in for SPDM – and practicing responses to contingency scenarios. OREs were intended to ensure all personnel were familiar with not just the tasks and hardware but the telemetry software, communication system, and protocols. Experiences from each phase of RRM, as well as testing with JSC and CSA flight controllers helped GSFC personnel create increasingly realistic simulations over time.

Flight Operations

A normal day of RRM operations lasted 16 to 20 hours; personnel at JSC, CSA, and GSFC worked multiple shifts a day. Each shift would start by reviewing the activities of the previous shift, configuring telemetry and video displays as desired for each position, powering up the on-orbit and ground robotic systems, and verifying communication links. Between shifts, each position would perform a handover with the person replacing them; this included a summary of the tasks accomplished, any problems encountered, and any upcoming changes to plans. At the end of the operations day, personnel would shut down the robotic systems, save video or images as necessary, and complete summaries of what had taken place during the day.

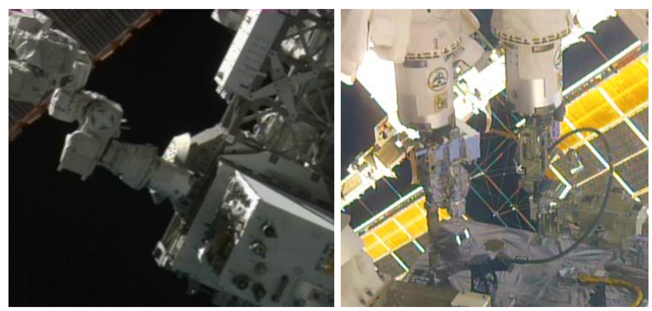

Figure 18. RRM (Left [4]) and RRM3 (Right [8]) On-Orbit Operations

5. Lessons Learned

This paper focuses on three categories of lessons that apply broadly to future robotic missions: designing the tools, cameras, and interfaces used to perform tasks; preparing for on-orbit operations; and conducting on-orbit operations.

Robotic Hardware Design

While robotic systems can execute tasks humans can perform, they typically cannot view or perform them in an identical way. The robot's capabilities and how the operator will observe the task should be key considerations when developing a concept of operations or design.

Tools, adapters, receptacles, and interfaces require clear status indicators—Indicators provide a variety of types of information, including alignment, orientation, contact, and tool or adapter mode. Mechanical indicators were preferred over electronic for reliability. Ideally, there should be some form of confirmation for each action taken, particularly if proceeding while in an unintended state would cause damage or have no recovery path.

The most critical RRM indicators verified that a tool or adapter was securely stowed after use. If unsecure hardware had been released by the end-effector or tool, it would have been nearly impossible to reacquire it robotically. To display stowage status, all tool stowage mechanisms featured Ready-to-Latch (RTL) indicators, which were actuated by tool contact with small plungers. Adapter receptacles included a push-to-turn mechanism with clear markers of location in the mechanism travel path.

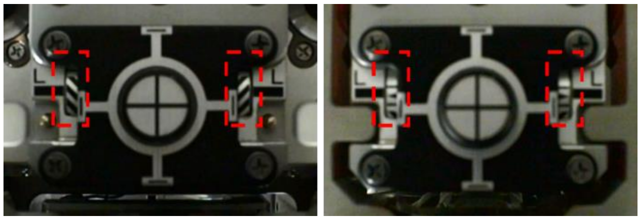

Figure 19. RTL Indicators (Left: Released, Right: Secure)

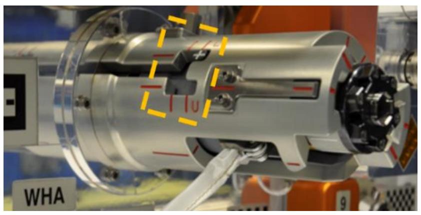

Figure 20. Example of Push-to-Turn Mechanism Status Indicator

Status indicators were always desirable but not always practicable. If the risk to the hardware was low, operational workarounds were implemented instead. RRM3's XCA had no status indicator for its launch lock, which was released through adapter actuation. During development testing with ground hardware, operators took advantage of the fact that the receptacle's push-to-turn mechanism could not be compressed when the launch lock was active to give visual confirmation of whether the launch lock had been released. Some operational workarounds, such as pull tests or dividing an action into multiple steps, could increase task time but allowed safe operations without increasing design complexity.

Most robotic tasks involved a tool or adapter contacting an interface, and indicators and alignment lines helped the operators accurately seat. Seating indicators should align with the robot's command frame axes to provide clear indications of misalignments and required corrections. Alignment lines should continue across surfaces whenever possible to reduce reading errors due to parallax.

Factor camera performance and field of view into design—During RRM Phase 1, engineers and robot operators had different ideas and preferences for the appearance of the tools and adapters. The best finish and color from a thermal engineer's point of view could be the most difficult for the operator to see in a camera view. To help guide the tool designers, the operators evaluated multiple colors and finishes for tools or adapters as well as indicator markings, given the typical background colors encountered during RRM operations (i.e., white beta cloth, reflective gold MLI, reflective silver Teflon tape, and empty space). Matte bead-blasted finish was preferred over glossy, the preferred anodize colors were clear, gold, and blue (in that order), and the minimum indicator line and dot sizes were 0.030 in. and 0.060 in. dia., respectively.

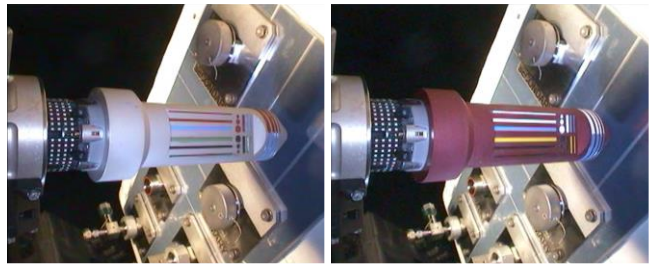

Figure 21. Tool Camera Views of Test Units (Left: Clear, Right: Red)

Preparation for the On-orbit Servicing, Assembly, and Manufacturing 1 (OSAM-1) mission showed that camera hardware and location are key variables when selecting tool colors and finishes. The tool cameras for all RRM Phases were set nearly in plane with the tool tip and with opaque diffusers on the attached lights. For OSAM-1, the tool cameras are mounted further back from the tool tip and with clear diffusers. Colors and balance vary with camera hardware, and contrast requirements vary with task. A new evaluation of the best colors and finishes should be performed for each new camera hardware configuration.

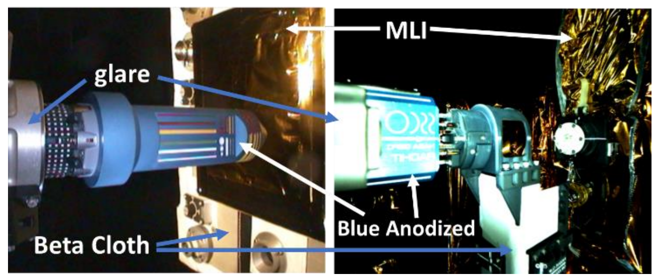

Figure 22. Tool Cameras Views of Various Materials (Left: RRM, Right: OSAM-1)

Where the tool cameras are mounted has a direct impact on tool and adapter design. If the cameras are part of each tool, as was the case with RRM, this increases overall mass and space required for tool storage and pushes the center of gravity (CG) further forward. In this configuration, there may be fewer tool design restrictions for static cameras, as they can be customized for each tool, however this still may not offer enough flexibility. The WCT's small field of view (FOV) allowed operators to see necessary details, but the tool's features could move outside of the FOV. Tool cameras with adjustable extension and pitch would have been beneficial in this case.

Figure 23. WCT Jaw in (Left) and out (Right) of Tool Camera View

If the cameras are part of the tool drive, as will be the case with the OSAM-1 mission, mass is saved, storage needs are reduced, and the CG is set further back. However, this imposes a greater need for hardware reliability since all tasks would be impacted by a camera failure. If the tool cameras are static, they impose length and visibility restrictions on all tool designs. If the tool cameras are adjustable, the length and visibility restrictions will be loosened, but mass and system complexity will be increased.

If machine vision will be utilized, this should be considered in the camera design. Sharper tool camera pitch angles intended to observe a tool tip, dashboard, or mechanical features are less than ideal for machine vision, providing a very oblique view of the marker. Accurate machine vision data requires precise feedback on the pitch angle and extension distance if adjustable camera mounts are utilized. Because machine vision recognition systems rely on comparisons of light and dark areas of the fiducials to identify them and estimate their position, they can be sensitive to harsh shadows or specular reflections. During RRM on-orbit operations, shadows cast during sunrise or sunset sometimes interfered with marker recognition. These shadows passed within a few minutes, but future missions with more static lighting conditions should carefully consider marker placement and lighting design. Tool camera lights can alleviate shadows but also may cause glare, especially on reflective markers, if opaque diffusers are not utilized.

In addition to adjustable extension and pitch, adjustable zoom and focus are also useful features. At different points in a task, different parts of the image are most important, such as the interface when performing alignment, or the tool dashboard during mechanism actuation. The focal depth of the RRM Phase 1 and 2 tool cameras was not large enough to simultaneously view both clearly. RRM Phase 2's VIPIR demonstrated the value of zoom capability when the tool was used to inspect of a very small mark on the SSRMS. [9]

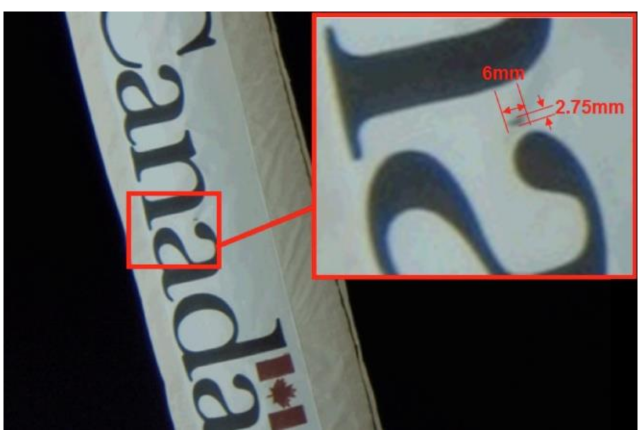

Figure 24. Imagery from VIPIR Inspection of SSRMS [9]

Using these lessons from RRM Phases 1 and 2, CPMs were designed for RRM3's MFT2 and the OSAM-1 mission with adjustable pitch and extension on both tool cameras and adjustable focus and zoom in one. RRM3 provided additional lessons for future servicing missions about the placement of adjustable cameras. At some pitch angles, the edge of the camera housing protruded further forward than the tip of the MFT2. This was not an issue when the tool was being used to actuate adapters but caused close clearances when the MFT2 was used on its own, such as to actuate a launch lock.

Design all surfaces at tip of robotic end effector or tool for potential contact—During RRM Phase 1, a tool camera on the WCT was very close to unintentionally contacting the interior of the RRM module during insertion and extraction (see Figure 25). The industrial robots used during ground testing were capable of more precise motion than the more flexible flight system. With tight clearances in the design, there was a potential for contact on-orbit. The aluminum tool camera housings were coated with Z93 white paint for thermal reasons. This paint is known to be sensitive to physical contact and can flake off if impacted, generating foreign object debris (FOD). Clearances, materials, and thermal coatings from RRM Phase 1 were considered in the tool camera design for both RRM3 and OSAM-1. The CPMs utilized by both missions are coated in a material that is not painted-on and does not have the potential to generate FOD if contacted. Additionally, the CPMs can be back-driven, so while contact is still undesirable, they will not immediately be damaged.

Figure 25. Unintentional Contact Point on the WCT

Single tools with multiple functions can be beneficial but require careful design—The MFT was designed from the start to have one tool perform multiple functions. This saved a significant amount of mass, with just one set of cameras and electronics instead of one for each function. OSAM-1 benefitted from this experience and will use a similar tool and a suite of adapters for a majority of the servicing tasks.

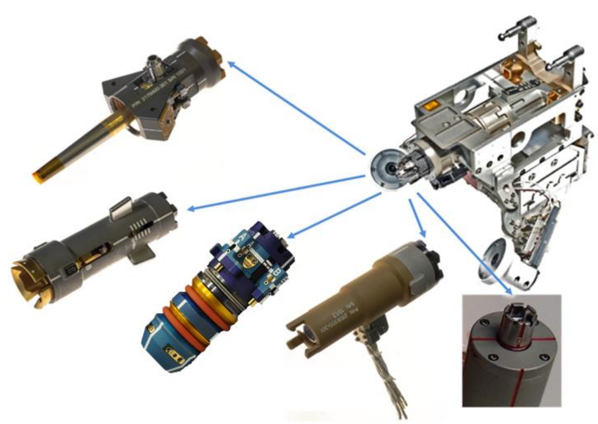

Figure 26. MFT with RRM Phase 2 Adapters and Interfaces

When modifying a single-function tool to perform additional tasks, designers may unintentionally introduce operational challenges. RRM Phase 1's WCT evolved to be three tools in one: pinchers for grasping MLI blankets or other small objects, a seam-ripper for Kapton tape, and a wire cutter. Adding functions to a single tool instead of creating new tools saved mass and volume but each function affected the others. The tape cutter and wire manipulation tool limited how close the gripper could get to a surface. When cutting a tape seam, the wire manipulation tool and cutter shroud prevented the operator from seeing what the cutter was about to encounter. Care should be taken if adding new features to an existing design becomes necessary.

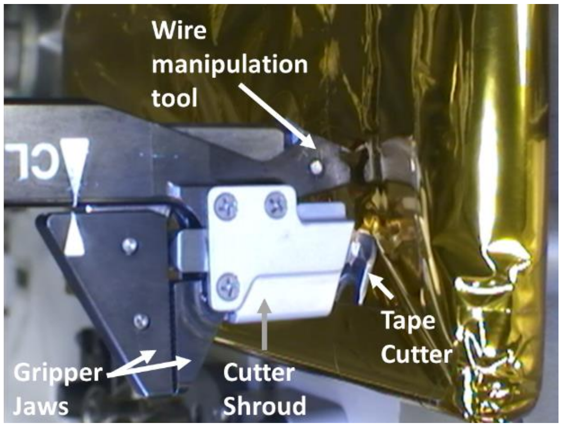

Figure 27. WCT Features as Seen During Tape Cutting Task

Consider both ground testing and on-orbit operations in design and component selection—It is critical that tool designers understand the robotic hardware, its software features, and how the tools they are designing will be used. When the ground and flight robotic systems differ, these differences must also be taken into account. Designers and robot operators should work closely and share their expertise for the best outcome.

Flight spare or EDU versions of the tools and adapters used for ground testing saw far more cycles during procedure development than the Flight units. RRM Phase 2's WHA was connected to the taskboard by a spring-reel tether to simulate an electrical harness. The spring on the ground mockup degraded in reaction force due to extensive use. This potentially could have impacted how reliably the ground unit could be used as one variable in troubleshooting activities during mission support.

The ground robots and software used for development had some key differences from SPDM. The receptacle design for RRM3's CCA required the robot to react to large axial forces during tool drive rotation to unlock or secure the adapter. This was not an issue for the more flexible SSRMS or SPDM and its software, but not possible for the rigid industrial robot used for ground testing. The ground robot could use an alternate method to complete the task, but this alternative was not something the flight robot could safely do. This design choice restricted flight-like task practice prior to and troubleshooting support during on-orbit operations.

Factor movement of flexible hardware into clearance analysis—During initial design of the robotic interfaces on the RRM and RRM3 payloads, CAD models of the tools and adapters were used to check lines of sight and physical interferences. The amount of compression required by the MFT or MFT2 drives often could not be determined until hardware testing began on a high-fidelity ground test simulator, at which point it was well into the design process to address potential interferences. During RRM3, interferences due to tool drive compression were resolved by changing how the tool was oriented relative to the interface. This extended the task and made visual alignment more challenging, as the tool cameras were no longer in line with the indicators.

Additionally, misalignments and accompanying loads were often greater on-orbit than during ground testing, which made achieving precise amounts of compression more difficult. During RRM Phase 2 on-orbit operations, the operations team realized prior to VPA insertion that unintended full compression of the MFT compliance band could potentially cause the tool to contact nearby interfaces. Replanning the approach maneuver in real-time to change the tool orientation caused an approximately 45-minute delay.

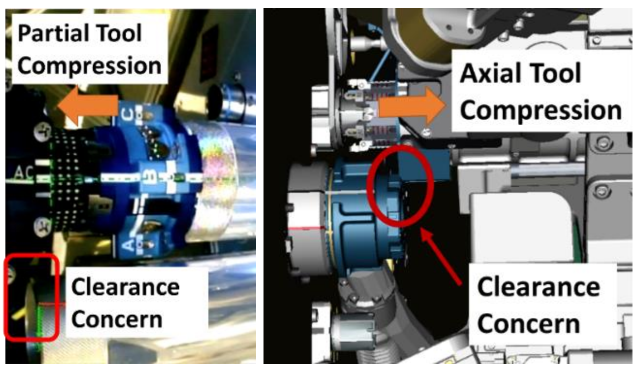

Figure 28. Clearance Concerns from Tool Compression with RRM Phase 2's VPA (Left) and RRM3's CCA (Right)

Future missions should perform CAD analysis with nominal and maximum compression states to evaluate potential interferences. The results should then be confirmed using flight-like hardware once it is available.

Procedure Development

Successful completion of RRM's objectives can largely be attributed to a) having high-fidelity reproductions of the RRM tools, payloads, interfaces, and cameras on the ground, and b) consciously choosing to spend time utilizing this hardware for procedure development, troubleshooting, and training prior to operations. Time is precious on-orbit, as it takes a great deal of coordination to reserve multiple days for robotic evaluations in the ISS's complex schedule. The hours spent practicing the tasks, documenting possible contingencies, and teaching operations personnel about mission hardware and tasks led to increased efficiency during operations. Through each phase of RRM, new lessons were learned about how to improve preparation or events confirmed that changes made since the previous phase had the intended result.

"Test as you fly" Principle—To develop task procedures and support troubleshooting during on-orbit operations, either high-fidelity simulations (including contact dynamics) or high-fidelity hardware is needed. For unique, short-duration missions like RRM, it can be easier to develop the hardware.

It is never too early in the development flow to have hardware available for ground testing. Evaluating newly available hardware just days prior to RRM Phase 1 on-orbit operations revealed a potential FOD issue. In this case, troubleshooting efforts led to a solution prior to operations, however, there is always the potential that there will not be a last-minute solution that meets mission or safety rules. Tasks should also be successfully performed from start-to-finish at least once during ground testing instead of only in parts.

In addition to testing the hardware and tasks, full telemetry, video, and communications paths should be evaluated. This can be difficult when elements are owned by other entities. During RRM Phase 1, the same camera hardware was used both in ground and flight tools, but the transmission path was different and the image quality was reduced on-orbit. The operations team struggled to discern whether valve threads were free of debris/damage during on-orbit operations.

If a complete path or task cannot be evaluated on the ground, additional time should be built into the on-orbit schedule in anticipation that issues will arise. During RRM3, the complete wireless video connection path for VIPIR2 could not be fully evaluated on the ground. The high fidelity mockup and VIPIR2 flight spare used for procedure development did not include wireless video hardware, and a piecemeal approach was used when testing the flight hardware. Configuration and connection issues with the wireless hardware and procedural errors were not discovered until on-orbit operations, and significant time was spent troubleshooting these problems, delaying the task timeline.

It is not always possible to construct or obtain identical copies of flight hardware and COTS or other similar equipment may be substituted. Robot operators should be involved during testing of flight hardware to help understand how ground versions may differ in appearance or operation. All differences between ground and flight hardware – including video quality, camera orientation, motor speeds, and colors or surface finishes (especially when items will be in contact) – should be clearly documented. Considerable time can be lost if the operations team believes they are encountering anomalies instead of known design or fabrication differences. The operations team should also be aware that if the ground hardware varies from the flight hardware, it may not be useful for troubleshooting efforts.

Effect of hoses and tethers—During ground testing, it can be difficult to discern the how hoses or tethers will affect the flight robotic system in microgravity. Gravity or the stiffness of an industrial robot system can mask or change these effects. RRM Phase 1's ENT was connected to a flexible hose that applied a small constant force in variable directions depending on tool position and the amount of hose deployed. This was not a concern for the rigid industrial robot used for ground testing, but unstowing the tool with the more flexible flight robot required a different command frame and resulted in closer clearances to nearby structures.

During RRM3 on-orbit operations, VIPIR2's boroscope became temporarily lodged in a curve the inspection line. Feeding out additional length did not overcome the issue, instead it began pushing the robot back away from the opening. This had never occurred during ground testing with a stiffer industrial robot and recovering on-orbit caused significant schedule impacts. For future missions, forces from ground testing should be compared to flight robot capabilities to determine if behavior on-orbit may vary.

Gravity effects during ground testing—During RRM Phase 1 ground testing, when the wire between two tertiary caps was cut, the wire fragment 'fell' to a specific location relative to the cap. The Tertiary Cap Adapter (TCA), which was used to remove the cap, was designed assuming the wire fragment would always be in this location. However, the fragment's behavior changed on-orbit without the effect of gravity. This incurred additional real-time workarounds by the operations teams to resolve this unexpected condition to install the TCA.

This experience led to increased awareness of how gravity may be affecting results. During RRM3 ground testing, the cryogen hose "bounced" as it was pushed through the CST's outlet perpendicular to the gravity vector. The end of the hose drooped with gravity and caused its ridges to catch on the tool's opening. There were concerns the hose tip might contact other structures or get caught on the robotic arm if it moved in this manner on-orbit. To test if the perturbations were just a gravity effect, a separate test apparatus was constructed to allow a hose to be pushed through the tool parallel to the gravity vector. The hose passed smoothly through the tool and reassured the operators. The hose behavior observed during on-orbit testing matched this result.

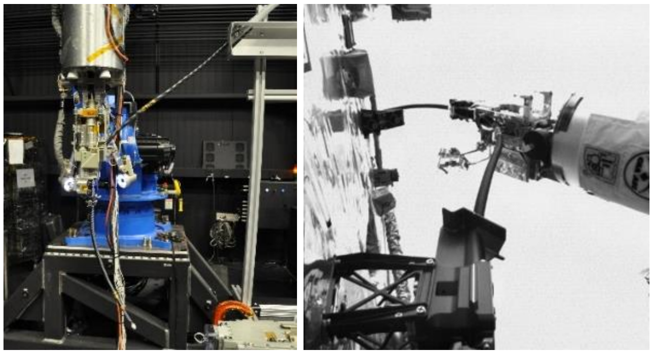

Figure 29. RRM3 Alternate Gravity Configuration Ground Testing (Left) and On-Orbit Operations (Right [8]) with the Cryogen Hose

Throughout RRM, multiple methods were used to negate or characterize the effects of gravity; each has advantages and disadvantages. For additional work on gravity negation for robotic testing, see [10]. The positioning equipment required for reorienting large and heavy mockups often requires a significant footprint within a facility, and hardware inside the mockup (such as motor controllers or cameras) must be well-secured. Some functions may be lost if only a portion of the mockup is replicated to make reorientation easier. In both cases, gravity can still affect the results; it is up to the test team to compare the various configurations and ascertain gravity's overall impact.

Helium balloons were used to negate the weight of a hose during an RRM3 evaluation of forces imparted to the robot due to hose stiffness. The hose's weight was effectively negated, but the robot's maneuverability was limited to prevent interference by the multiple 24" diameter balloons.

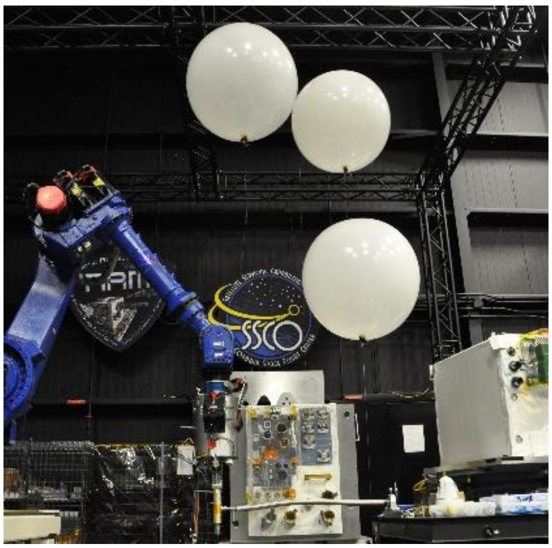

Figure 30. RRM3 CCA Hose Force Testing with Helium Balloons

On-Orbit Operations

Even when considerable time is devoted to ground testing and preparing the operations team, on-orbit operations will always have some differences. The schedule is more limited, there are more people observing, and there are higher consequences for anomalies or errors. It is critical that the operations team has the tools and knowledge to handle inevitable unexpected events efficiently and effectively.

Operations team roles and protocols—Some aspects of voice communication within the GSFC operations team and between the two operations teams were very well defined. The structure that limited which members of each team could talk to the other team prevented controllers from being distracted by conversations they did not need to focus on. However, there were still a few issues. Indirect communication through the Ops Lead sometimes led to misinterpreted instructions and additional time being spent relaying corrections. A more efficient method was to have the SME answer ROBO directly after internal discussions within the GSFC team resulted in a solution. To further improve efficiency, it was important for the Ops Lead to clearly establish the expected duration of the direct communication (such as until the completion of a particular procedure step or until permission was explicitly revoked). This would avoid having the SME repeatedly verbally verify whether they could answer ROBO directly.

Importance of quality camera views—Frame rate, resolution, and number of downlinked camera views may be outside the control of those designing the robotic system or tools, but they should advocate for as high of capabilities as possible. The minimum required to perform a task, such as to align with an interface, will most likely be inadequate in off-nominal situations, such as inspecting for thread damage or FOD after an unsuccessful seating attempt.

The ideal camera frame rate is 24 fps; the minimum that should be used for telerobotic operations is 10 fps. During early RRM3 operations, the Pan/Tilt Camera (PTC) was operating at approximately 1/7 fps due to downlink restrictions. This could be utilized for judging alignment but not for observing motion. As the CCA was locked into its port, its hose moved in an unexpected way. The low frame rate meant the PTC could not provide useful data for troubleshooting.

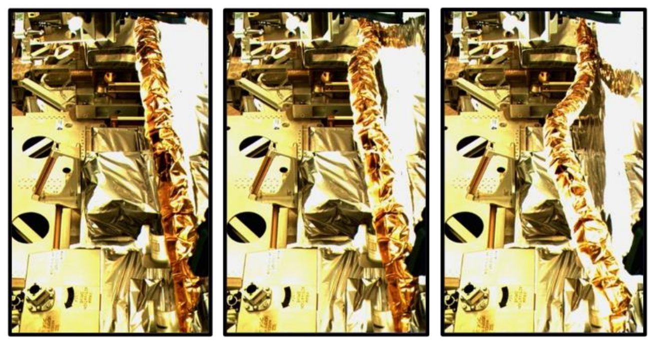

Figure 31. Consecutive PTC Frames during RRM3 CCA Operations

Robot operators need to contend with constantly changing lighting conditions on-orbit. During RRM Phase 1 MLI blanket cutting activities, it was difficult to see the tape seam in low on-orbit lighting. Lights from the tool and external ISS cameras could not be adjusted in intensity as desired. Based on this experience, the CPMs, PTCs, and fixed situational awareness cameras used for RRM3 and the OSAM-1 mission include adjustable intensity lighting.

Each RRM tool had two cameras spaced 90 degrees apart to allow operators to visually determine alignment in three dimensions. However, SPDM's video system has a single line to return video from end-effector or payload cameras. Switching between the two tool cameras required multiple commands and added time to on-orbit operations. Sometimes flight controllers decided to skip switching the cameras if they could reasonably assume the alignment was as desired using external cameras or system telemetry. Control systems that allow changes between multiple options should be as simplistic as possible to improve efficiency and reduce the likelihood the user will opt to omit verification steps.

If external limitations on the video system cannot be altered, flexibility can be built into the robotic system or tools. Multiplexing parts of two tool camera views can overcome the issue of only having one video line. Fixed downlink bandwidth can be overcome by adjusting frame rate, resolution, and/or windowing based on the circumstance. The initial low frame rate for RRM3's PTC was later improved by subsampling the images. Downlinking multiple camera views with subsampling and higher frame rate can be used when the robot is in motion. A single camera with high-resolution and a low frame rate can be downlinked when judging alignment or during troubleshooting, since the robot will be stationary.

Real-time data plotting—Strip plots of force and torque data are essential for robotic operations involving contact, hoses, or tethers. Plots should scroll continuously to maintain at least one minute of historical data instead of resetting at set intervals. Standard colors for frame axes should be used throughout the robot control software, including with plots. Altering and especially swapping colors between various applications can lead to read errors. Automatically rescaling the vertical plot axis based on the current maximum values can be useful, but the operator should have the ability to disable this feature if desired, as it can cause read errors if they do not notice the range has changed. Experiences from RRM influenced the control software used for OSAM-1 and other future missions.

Reference documentation and tools—Several products were developed, either preemptively or as RRM experience was gained, that helped the GSFC team during on-orbit operations.

Tool & Interface Handbooks described the function, features, and overall dimensions of each RRM tool, adapter, and interface. Each feature on the tool was given not just a name but a reference letter. Verifications and other instructions in the procedures used the terminology and reference letters from the handbook to allow the reader to easily look up any features that were unfamiliar. For future missions, including additional dimensions of specific features (e.g., the width of the tool tip) would be beneficial. Knowing the size of objects visible in the tool cameras can help the operators determine required movement distances during small tasks like correcting alignment with an interface.

Posters and photo books were created with high-quality images of the tools, adapters, and taskboards and placed in the control centers to assist controllers and engineers during troubleshooting. Each tool or adapter only had one flight spare, which resided in the STC. The posters and photo books allowed any other member of the team to also see the hardware's details.

Including detailed verification information in procedure steps also improved efficiency. The operator was provided with as much data as possible, such as that being within a range was just as acceptable as being perfectly aligned (less time would be spent making corrections) or that an alternate camera could give necessary information (less time would be spent switching back and forth).

Alignment aids—Most RRM tasks involved aligning a tool with an interface or stowage receptacle. Virtual static overlays were designed to assist controllers with visual alignment. These simple graphics belied the coordination and effort that went into creating them. The two operations teams used different video systems; each had a different resolution and required a different image format. Small details like these were easy to overlook or underestimate, so testing and correcting the overlays in advance was critical to prevent lost time on-orbit. The addition of keying features allowed any user to verify that the overlays were positioned and scaled appropriately on the screen. Once the MFT2 was introduced, these features also helped to verify the CPMs were pitched as desired. The overlays also included features such as distance markers and reminders of the control frame orientation relative to the camera.

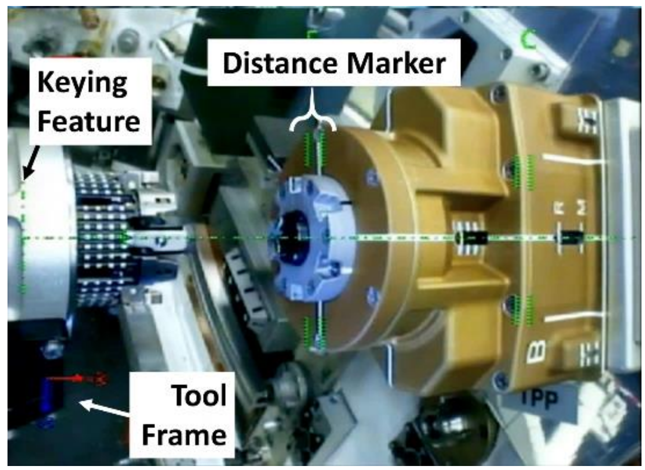

Figure 32. MFT Overlay Example from RRM Phase 2

Some overlay features may be less effective with adjustable cameras unless exact mechanism positioning is known. For example, if CPMs are both pitched and extended, distance markers may be invalid if there is no telemetry to confirm the amounts of mechanism motion.

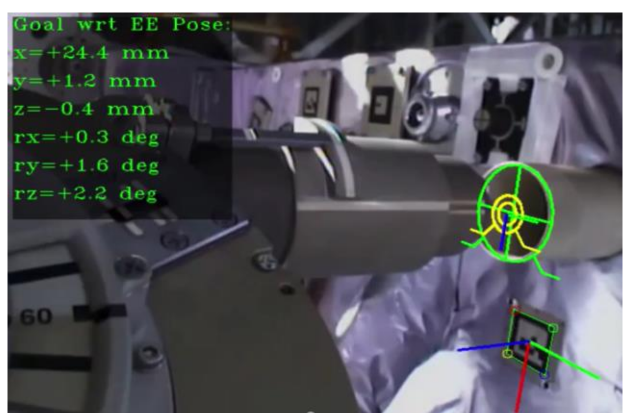

Figure 33: Machine Vision Information Display During VIPIR2 Alignment with Inspection Port

All three phases of RRM provided opportunities to evaluate machine vision software and fiducials that can assist operators during future on-orbit robotic tasks. These include alignment with interfaces, tool stowage and retrieval, identification of interfaces of interest, and calibration of cameras to ensure accurate recognition. The software information display shown in Figure 33 was utilized during RRM3 VIPIR2 operations and provides the position and orientation offset between the tool tip and the interface. The display also identifies the fiducial being observed (lower right) and the interface (center right). Following the success of these evaluations, future robotic missions should consider using machine vision data as the primary alignment method.

Machine vision relies on accurate knowledge of the camera and lens being used, including focal length, field of view, resolution, and inherent distortion in the lens. It is preferable to fully characterize cameras and lenses prior to launch. However, if this is not possible or additional cameras need to be characterized after launch, the on-orbit camera calibration performed on RRM3 was accurate enough to contribute less than 2 mm of error to the estimate of fiducial position. Future robotic missions should include a calibration pattern on the payload, such as in Figure 34, to allow for on-orbit calibration.

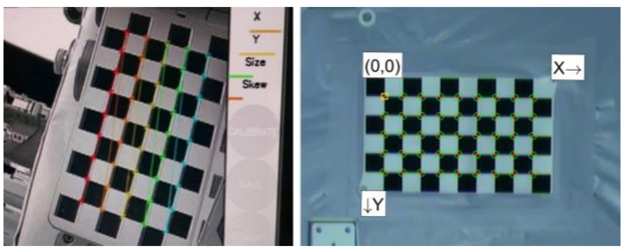

Figure 34: Machine Vision Calibration Patterns from RRM Phase 2 (Left) and RRM3 (Right)

Precisely defining features on the tool relative to the camera and features on the module or spacecraft relative to the fiducial are key for calculating alignment using machine vision. These items should be metrologized as accurately as possible. When time permits, it can be beneficial to measure additional features. During RRM3, machine vision scenarios were initially only created for the ideal features for each task. When alternative plans or contingencies arose, additional scenarios had to be calculated based on existing data and CAD models, rather than from the as-built hardware. This introduced additional sources of error into alignment estimates that could have been eliminated with more thorough metrology prior to launch. Future robotic missions should develop a consistent frame guide that establishes the location of all fiducials and all interfaces relative to a consistent spacecraft frame, the location of all cameras, accounting for any adjustable lens parameters and camera axes, and all tool tips or possible contact surfaces relative to the robot end effector. This will maximize flexibility in what cameras and markers are used during operations.

High-fidelity hardware to support on-orbit operations—It was important to have high-fidelity hardware support not just for procedure development but also for on-orbit operations. The solutions derived from troubleshooting with the ground hardware and robotic system prevented on-orbit operations from being terminated when unexpected issues arose. This hardware was also critical when on-orbit operations proceeded swiftly without issues. During RRM Phase 2, there was time remaining on the final operations day after completing all planned objectives. The JSC and CSA flight controllers offered to perform additional testing with VIPIR if a new procedure could be developed during the couple of hours it would take to maneuver SPDM and the SSRMS to an apporpriate location. A new task and procedure had never before been developed in so little time, but the robot and tool SMEs at GSFC used ground hardware in the STC to test and document small maneuvers and tool actuation. The procedure was emailed to the flight controllers who seamlessly executed the steps. If the high-fidelity hardware had not been set up and ready to support, that operations time and the knowledge gained from it would have been lost.

Increased task duration on-orbit—Operations schedules were always planned around the number of tasks to be performed. Since robotics personnel at JSC, CSA, and GSFC only worked scheduled shifts (not 24/7 coverage), it was important to estimate as accurately as possible how long tasks would take. Timing from ground testing was always a starting point but there were several significant differences with on-orbit operations. Most ground testing was performed using hand controllers to maneuver the robot, while all on-orbit maneuvers were point-to-point. Hand controllers allow the operator to instantaneously adjust speed and do not require a pre-motion estimate of the distance to be traveled. It is easy to under- or over-shoot with point-to-point motions, requiring multiple commands to be input, verified, and executed. During ground testing, the operator nominally worked shoulder-to-shoulder with a tool or hardware engineer. Questions about the task did not need to be relayed up a team hierarchy or over communication channels like during on-orbit operations. The higher penalties for mistakes with flight hardware also led to more time being spent communicating and verifying commands before execution.

In addition to the recommendations in previous sections, other steps can be taken to improve efficiency during future missions. Groups of commands that will be repeated regularly, such as to turn on or off hardware, should be scripted together to allow just one command to be sent instead of many. Each inputted command takes additional time and provides a chance for an error to be made. Anomalies seen or considered during ground should be documented with the appropriate response to reduce on-orbit troubleshooting. Procedures should include expected task or step durations, so it is easy to decern if a task is taking significantly more than the planned (or allotted) amount of time. The operations team should also have planned breakout points to prevent unexpected events from disrupting the entire timeline. If a task takes more than a certain amount of time or is not completed by a particular time, the team should agree to switch to a backup plan and move on so other tasks are not sacrificed.

6. RRM's Impact on Subsequent Missions

RRM demonstrated how other missions could utilize the ISS for technology development. In 2017, a relative navigation payload called Raven was launched and mounted on the ISS. It contained visible, infrared, and lidar sensors used to acquire and track cargo spacecraft as they approach the station. [11] Evaluating and maturing this technology is key for successful rendezvous during OSAM-1. Additionally, the relationships between GSFC and JSC engineers fostered through RRM led to other joint projects. In 2015, the Robotic External Leak Locator (RELL) was launched to the ISS to assist the crew and flight controllers with detecting dangerous ammonia leaks. Using a robotic tool reduced the amount of time astronauts must spend on spacewalks to find and repair leaks. RELL successfully located a leak in 2017 and a second unit was launched to the station in 2019. [12]

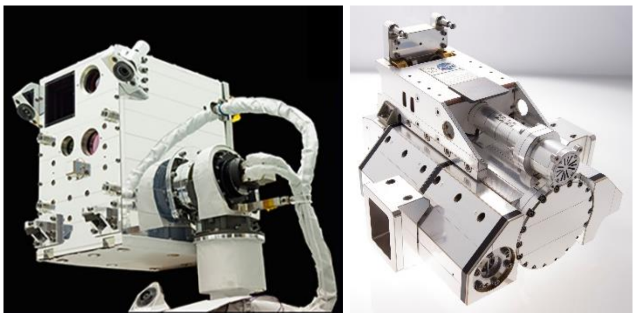

Figure 35: Raven (Left [11]) and RELL (Right [12])

Other GSFC missions have benefited from the knowledge and experience gained from RRM. The Phase 1 WCT and SCT have evolved into adapters for OSAM-1, saving mass and storage volume. On-orbit operations demonstrating that a robotic tool could transfer a fluid in zero-g were followed by ground evaluations that showed a robot could safely transfer highly corrosive satellite propellent while being operated from hundreds of miles away. These experiences influenced the tool and task design for OSAM-1. RRM also shaped the tools and methods used for developing OSAM-1 robotic procedures, as well as operations team protocols and composition.

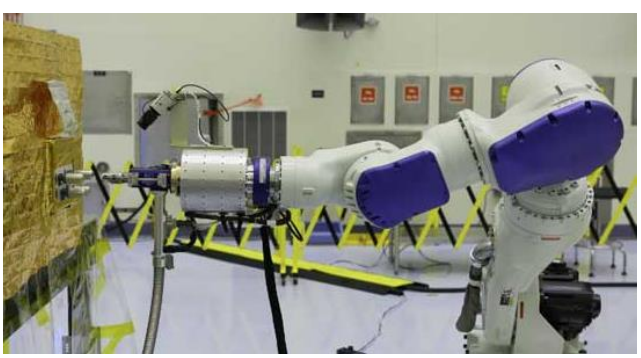

Figure 36: Robotic Oxidizer Transfer Testing at Kennedy Space Center's Payload Hazardous Servicing Facility [13]

The majority of RRM's procedure development and troubleshooting efforts utilized industrial robots instead of more expensive and complicated robotic systems. These robots proved to be an excellent low-cost means of accurately positioning and actuating servicing tools. Industrial robotic systems are also being utilized for OSAM-1, Mars Sample Return, and demonstrations of future servicing techniques and hardware.

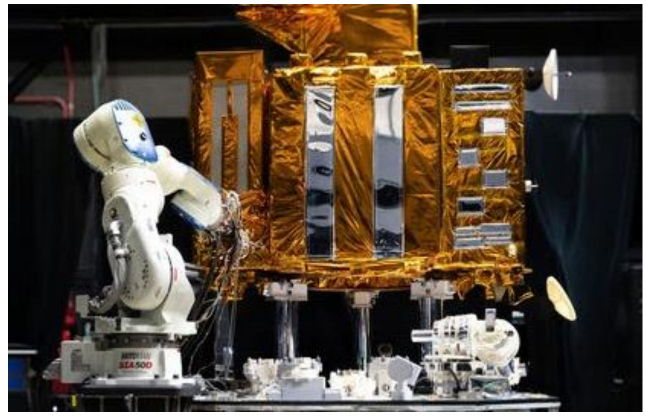

Figure 37: OSAM-1 Servicing Testing Utilizing an Industrial Robot

RRM demonstrated significant advancement in the use of machine vision technology in space. Future robotic missions can use this technology for more accurate alignment with interfaces and more efficient operations. Adding fiducials to key locations, such as near potential grasp points or fuel valves, is a low cost and low mass modification that can have a significant positive impact on serviceability. The RRM work has informed decisions to include fiducials on a variety of spacecraft, including OSAM-1, the Magnetospheric Multi Scale (MMS) Mission, the James Webb Space Telescope (JWST), and a variety of commercial satellites.

Acknowledgements

The authors would like to acknowledge the support of NASA and the Exploration & In-space Services Projects Division. Thanks also to the Robotics Operations Group at JSC and CSA and their supporting engineers at CSA and MDA. The work reviewed in this paper was performed under the MSES, OMES and OMES II contracts.

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BIOGRAPHY

Zakiya Tomlinson received a B.S. in Aerospace Engineering from the University of Maryland, College Park and a S.M. in Aeronautics & Astronautics from MIT. She is a robotic operator and training lead with NASA's Exploration and In-Space Services (NExIS) Projects Division at Goddard Space Flight Center, utilizing a variety of robotic systems to evaluate designs and techniques for servicing and sampling missions. Prior to joining NExIS, she supported pre-launch testing and procedure development for Landsat 8 and robotics training for the International Space Station (ISS) program. Her academic research focused on spatial reasoning skills and performance during telerobotic training.

William Gallagher received a B.S. in Aerospace Engineering from the University of Notre Dame, and a M.S. in Aerospace Engineering and a Ph.D. in Robotics from Georgia Tech. He is a robot operator and senior robot systems engineer with NASA's Exploration and In-Space Services (NExIS) Projects Division at Goddard Space Flight Center. He supports development of robotic technologies for remotely servicing satellites, in-space assembly and manufacturing, and exploration of small bodies, including On-orbit Servicing, Assembly, and Manufacturing 1 (OSAM-1), the Asteroid Redirect Mission (ARM), and the Robotic Refueling Mission (RRM). His academic research focused on compliant control of robots, especially in the presence of physical human-robot interaction.

Justin Cassidy received a B.S and M.S. in Mechanical Engineering from Catholic University of America. He has managed several projects including NASA Goddard Space Flight Center's efforts for Alpha Magnetic Spectrometer (AMS) EVA repair and the Robotic Refueling Missions (RRM). These utilized his expertise in developing and testing robotic tools/end effectors, stowage and delivery systems and flight payloads for space launch systems.

Brian Roberts received a B.S. in Aerospace Engineering from Case Western Reserve University and a M.S. in the same field from the University of Maryland, College Park. He is the Deputy Director of NASA's Exploration and In-Space Services (NExIS) Projects Division at Goddard Space Flight Center. Prior to coming to Goddard, he spent 6 years as a research engineer at the University of Maryland, working on teams that developed and tested various robotic systems ranging from those designed to service satellites and fly on the Shuttle, to those that can assemble and disassemble themselves in space, to those that autonomously find and sample life at the bottom of the ocean.

Kristen Facciol received a B.A.Sc in Aerospace Engineering from the University of Toronto. She is a Robotics Flight Controller with the Canadian Space Agency (CSA), working jointly with the Flight Control Team at NASA's Johnson Space Center. The robotics team is responsible for the preparation and execution of robotics operations onboard the International Space Station (ISS). Prior to joining the CSA, she spent over 7 years as a Systems Engineer at MacDonald, Dettwiler and Associates (MDA), working on projects focused on on-orbit satellite servicing, supporting real-time operations on the ISS, and training astronauts and flight controllers from various space agencies.

Joseph Easley received a B.S. in Aerospace Engineering from the University of Maryland, College Park, and is the Robot Operator Group Lead for NASA's Exploration and In-Space Services (NExIS) Projects Division at Goddard Space Flight Center. In recent years he has supported hardware development, I&T, and flight operations for the various phases of the Robotic Refueling Mission (RRM) demonstrations aboard the International Space Station (ISS). He is currently supporting robot operations development for the On-orbit Servicing, Assembly, and Manufacturing 1 (OSAM-1) mission along with various other NExIS projects.