Robotic Refuelling Mission

Demonstrating Satellite Refuelling Technology on Board the ISS

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Abstract

Over the last two (2) years, the Canadian Space Agency (CSA) has been working in partnership with NASA Goddard Space Flight Center (GSFC) to demonstrate the technical capability to robotically refuel satellites in orbit that were designed for ground fuelling only. In order to demonstrate this capability, Goddard has designed and built a set of tools and adapters to be used by the Canadian robotics on-board the International Space Station (ISS).

The Robotic Refueling Mission (RRM) completed phase 1 of operations in May 2013. This paper provides a summary of the on-orbit operations for phase 1 and discusses the results of the robotic operations over the course of the various tasks performed via ground controlled tele-robotics. The focus of this paper is on the performance of the Canadian Robotic systems as opposed to the performance and capabilities of the tools.

Figure 1: SPDM in Position at RRM Worksite

1 Introduction

The operations for the RRM were split into five (5) sessions which were completed over the course of several months, with each session consisting of several days of operations.

Table 1: RRM Operations Timeline

	Timeframe	Operations
1	Sept 2011	Launch Locks & Vision Test
2	March 2012	Coolant Valve Tasks Part 1
3	June 2012	Coolant Valve Tasks Part 2
4	January 2013	Fuel Transfer
5	May 2013	Tertiary Tasks

All RRM operations were conducted via Ground Control with team members supporting from Johnson Space Center (JSC) in Houston, CSA in St. Hubert and GSFC in Maryland.

2 Initial Operations

The first session comprised a checkout of the tools after launch and a simple vision test. The next two (2) sessions used the Multifunction Tool (MFT) with several adapters to perform tasks that would be required for on-orbit servicing of satellites not designed for robotic refueling on-orbit.

In the first Coolant Valve Task Session (CVT1) the Multifunction tool was used to release the seven launch locks on the MFT adapters so that the adapters could be removed in the following session (CVT2). The Wire Cutter Tool (WCT) was then used to cut two (2) wires. The first wire was strung between two (2) T-Valves, and the second was on the Ambient Cap.

Day 1 (June 19, 2012)of the operations saw the Special Purpose Dexterous Manipulator (SPDM) retrieve the Multi-Function Tool (MFT) from the tool bay and pick up the first of four (4) adapters – the Tool Valve Adapter (TVA). There were some minor issues with the interaction of the MFT and the OTCM torquer. After completing a characterization of this interaction and developing a model to apply to subsequent on-orbit operations involving the MFT the operations proceeded with no issue. The T-Valve was successfully removed and stowed in the T-Valve Receptacle on the second attempt. The Ambient Cap Adapter (ACA) was unstowed in preparation for the next day's operations.

Figure 2: One of the RRM tools being removed from the RRM ToolBay

Day 2 (June 20, 2012) saw the removal of the Ambient Cap. During the operation, the wire on the cap that had been cut during CVT1 had drifted over the cap and there was a concern that the ACA may not seat properly. The operators used the ACA to bump the wire out of the way. After backing off, the wire drifted over the cap again. The operators used a modified approach to seat the ACA on the cap and the cap was successfully untorqued. The Plug Manipulator Adapter (PMA) was then extracted.

Day 3 (June 21, 2012) wrapped up RRM CVT operations by manipulating the plug installed at the worksite where the Ambient Cap had previously been removed. The plug was pulled up using the PMA, then the PMA was stowed. After reviewing the data, Goddard requested a second look at the plug. The operators re-ran the steps to move into position to view the plug; Goddard verified that the plug had indeed moved.

Next, the Tertiary Cap Adapter (TCA) was extracted and used to check out the Tertiary Cap Receptacle (TCR). Following the checkout, the MFT was stowed with the TCA still installed on the MFT. The final step was to grasp the Extravehicular Robotics (EVR) Nozzle Tool (ENT) and check out the ENT cameras in preparation for refueling operations.

2.1 Results of CVT Operations Discussion

Overall the RRM CVT operations were carried out very smoothly. The main challenge for the MSS in all these tasks was to accurately position the tip of the tool with respect to the worksite. Originally the SPDM was designed to work with contact geometries which supported a +/-6 mm, 2 degree envelope. However as RRM is representative of interfaces, not designed for robotics, many of the coolant valve task operations performed required the envelope to be closer to +/-1mm, +/-1 degree.

The key to the success of these operations was in the many months of analysis preceding the operations. This included analyzing the results of real-time and non-real-time computer simulations as well as hardware testing [1]. The results of the analysis were used to update operating procedures for the mission as well as to fine tune SPDM control parameters for optimal performance.

Reliable visual cues were also critical in aligning the tool to the worksite. Relying solely on Frame of Resolution (FOR) digital telemetry did not provide the accuracy required. The RRM tool cameras provided excellent views and visual cues to assist the operators to align the tool.

Figure 3: MFT positioned to acquire adapters for CVT1 operations (photo credit NASA/CSA)

In order to completely align the features of the adapters with the features on the worksite, the MFT required very small motions of the SPDM torque mechanism. The torquer was designed to fasten and unfasten tie down bolts on On-Orbit Replaceable Units (ORUs), not for high accuracy mechanism actuation. In particular the torquer is designed to back-off a short distance once the operation is complete.

This back-off normally prevents the socket from binding on the fastener when the socket is retracted.

Given that the torque was being used to actuate a mechanism, the SPDM used a special set of parameters which set the back-off to zero to prevent this motion This case was proven during freespace checkout of the WCT in CVT1 and updated fir CVT2 operations.

Based on the performance in CVT1 operations, several of the SPDM control parameters were modified to allow for better control in small commands in CVT 2 Operations. Including the removal of the back-off as discussed. Modifications were also made to procedures, including the development of contingency procedures to accommodate the required small turn counts in different operations.

The ACA operations involving the wire that drifted up also highlighted the need for alternate methods and contingency procedures that can be adapted, as required, to the situation at hand. Ground controlled robotic operations are typically highly scripted; however these specific contact operations require the ability to adjust on the fly while upholding safety guidelines. The use of Force Moment Accommodation (FMA) in this particular case meant that the tool was protected from contact loads that could damage the hardware, even though the exact contact scenario had not been analyzed.

3 Fuel Transfer Operations

The main RRM operations began again on January 14th, 2013 with the showcase operations of actually accessing a valve and transferring fluids. Initially, five (5) days of operations were planned, however six (6) days of operations were finally carried out over two (2) weeks. The fuel Transfer operations required the SPDM to manipulate a tethered tool in freespace involving contact operations, a first for the SPDM.

The first day, the SPDM unstowed the WCT and used it to cut the wire on the Tertiary Cap that covered the fuel valve to be accessed. Once the wire was cut, the other arm was used to unstow the MFT, which was already equipped with the TCA from the previous (CVT2) operations. Some difficulties occurred while unstowing the MFT due to some initial misalignments in the system which caused an increase in the forces required to unstow the toool; The tool was successfully unstowed after subsequent commands reduced the loads and the MFT was used to remove the Tertiary Cap.

Figure 4: The ENT with Tether Shown in Extracted Position

Day 2 began with stowing the TCA back into the MFT Adapter Receptacle (MAR). However, following the TCA insertion into the MAR, MSS operations were halted for reasons unrelated to RRM.

Day 3 RRM operations resumed on January 17th with the WCT cutting two (2) more wires - one on the Actuation Nut and the other on the Safety Cap. Once the wires were cut, the WCT was stowed back in the RRM, as was the MFT. The SPDM then grasped the Safety Cap Tool (SCT) to remove it from the RRM Tool Bay. However, when the Umbilical Connector was commanded to mate, the SPDM umbilical stalled during insertion. The SCT was ungrasped and the Umbilical was checked out before manoeuvring into a park configuration for the weekend.

RRM Operations resumed on Day 4 with the successful mate and unstow of the SCT. The SCT was then used to checkout the Safety Cap Receptacle (SCR), which would be used during the next set of operations. The SPDM then used the SCT to remove the Safety Cap on the Fuel Valve. Once the cap was off, the SCT was stowed back in the RRM with the cap secured in the tip of the tool as planned.

Day 5 of Fuel Transfer operations saw the MSS setup for the ENT operations by using Arm2 to grasp the Express Logistics Carrier (ELC)4 Nadir H-Fixture for stabilization. Since the SPDM sits at the end of the 17m long SSRMS, external loads such as the ENT tether can cause unwanted deflections in the SSRMS. Figure 4 shows the MSS in configuration for non-ENT RRM operations.

Figure 5: MSS Configured for RRM Operations at ELC4 in Unstabilized Configuration

Figure 5 shows the MSS stabilized. Arm 2, the stabilization arm can be seen on the right while Arm 1, on the left is shown holding the ENT.

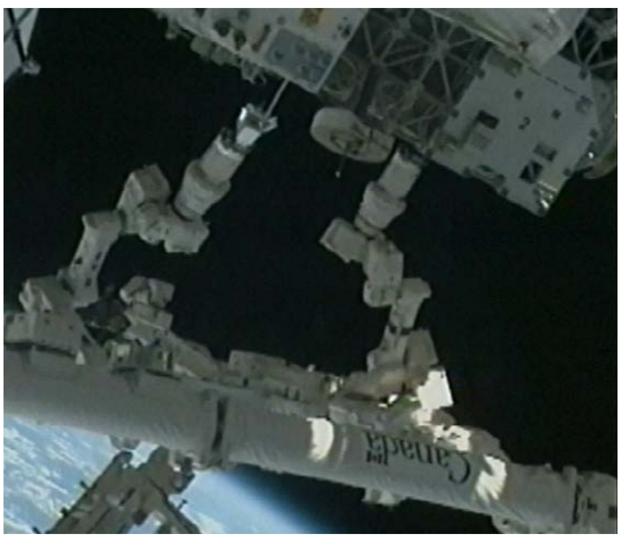

Figure 6: MSS Stabilized for RRM Operations at ELC4

Arm1 then grasped the ENT and removed it from the tool bay. Once the ENT was unstowed, the operators manoeuvred the tool to help characterize the behaviour of the system while manipulating a tethered payload, particularly the initial transients at start of motion. The results matched the motion predicted by analysis.

Fuel Transfer operations were carried out on Day 6. Arm1 manoeuvred the ENT into position over the valve. Using FMA, the ENT was secured on the valve, and the team at GSFC and Marshall Space Flight Centre successfully commanded a benign fluid representative of fuel, to be pumped continuously through the ENT around a fluid loop.. Once the fuel transfer was complete, the ENT was backed-off and successfully stowed in the RRM. Arm2 released the H-Fixture and the MSS was backed-off to a park configuration.

3.1 Fuel Transfer Operations Discussion

The entire ENT operation had been heavily pre-co-ordinated with teams at MDA, CSA, JSC and GSFC all contributing to the procedures development. The previous operations experience resulted in improved communications among all groups. This improvement aided the analysis inputs and results discussion as well as the procedure development. Consequently, the on-orbit system response was exactly as predicted by analysis. This excellent collaborative team effort contributed greatly to the successful operations.

Manipulating a tethered payload, in this case the ENT, was the primary challenge for the MSS. The tether forces induced by the ENT hose necessitated using the second arm on the SPDM to stabilize the MSS. In the unstabilized configuration, simulations conducted at CSA showed that the ENT hose could cause the tip of the tool to deflect significantly due the flexibility in the system, which is dominated by the flexibility in the SSRMS. Using the second arm to grasp a fixed point on the station eliminated the flexibility from the SSRMS and thus eliminated the majority of the unwanted tip deflections.

The remaining tip deflections were due primarily to transients occurring at the start and end of motion. Typically the SPDM exhibits some small off-axis transients; however the off-axis transients observed while handling the ENT in simulations were significantly larger than typical. Analysis showed that these higher transients could cause the ENT to miss the valve when moving in, if they were not accounted for in the procedures [2]. The solution was to position the ENT with enough clearance to the valve such that the line tracking algorithms had enough space to recover to the nominal trajectory prior to contact.

The ENT tether forces were high enough to be reacted to by the FMA control systems and to mask the forces that were applied at the interface. The solution to this was to recalibrate the Force Moment Sensors (FMS) while holding the ENT in freespace. This effectively zeroed out the forces from the tether for the ensuing contact operations.

Prior to unstowing the ENT however, the FMS had been calibrated without the tether forces present. In order to account for this, several control parameters had to be modified in order to safely extract the ENT from the RRM. In order to determine the proper settings, MDA performed a combination of hardware testing [2] and computer simulations. This resulted in updated control parameters; most notably the command frame was offset to account for the pull force from the tether.

Review of the data after the operations determined that the difficulties seen unstowing the MFT from the RRM toolbay were due to higher than expected off-axis loads. These loads, which were higher than seen previously, resulted in FMA taking longer than expected to reorient the tool for extraction and timing out as a result. Subsequent tool operations were updated to allow for a longer FMA response time at steady state and procedures were updated to account for letting FMA run longer.

4 Tertiary Tasks

The final session of RRM Phase 1, which commenced on May 1, 2013, involved performing several operations useful for on-orbit servicing of satellites, including fastening/unfastening screws, removing Science Monitoring Area-Adapter (SMA-A) caps and manipulating some Kapton Multilayer Insulation (MLI). These operations were scheduled for five (5) days, spanning a two (2) week period.

Day 1 (May 1, 2013) of the Tertiary Tasks Operations saw the SPDM unstow the WCT and the SCT. The operations were delayed somewhat by jittery video due to video synchronization errors (Figure 7) with the tool cameras using the newly updated KU system on the ISS. The video team at JSC managed to set the system to a useable configuration and the operations continued. The SCT was used to successfully deposit the Cap removed in the previous session into the SCR. The SCT then retrieved the SMA-A, however after retrieval, the video degraded and operations were halted as the camera views were no longer usable.

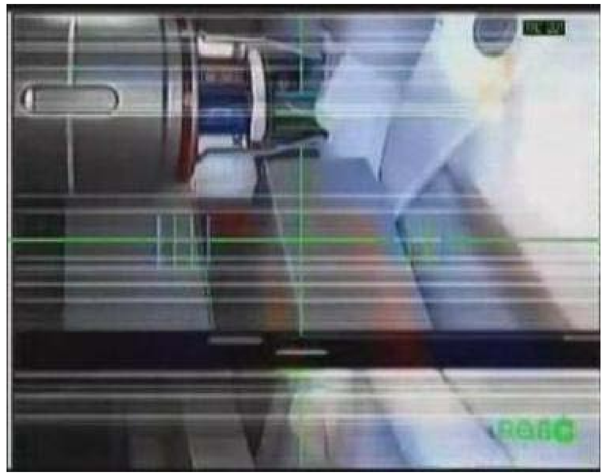

Figure 7: Degraded Video due to Synch Issues

Operations resumed on the following day, May 2, 2013. During the pause in operations, JSC managed to re-tweak the video settings such that, while not perfect, they were sufficient to allow operations to continue. The SCT with the SMA-A adapter was used to remove two (2) SMA-A caps. The entire adapter, along with the caps, was deposited in the SCR. Six (6) attempts were required to seat the SCT on the Torque Set Adapter (TSA) (Figure 8), due to difficulties aligning the tool with the TSA well enough to achieve full seat. Once the TSA was successfully retrieved by the TSA two (2) screws were unfastened and the MSS was backed-off to a park configuration for the weekend.

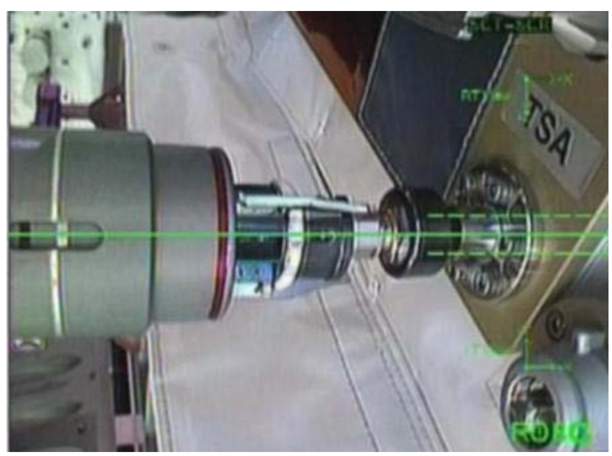

Figure 8: SCT seated on the TTSA

Day 3 (May 6, 2013) operations resumed with re-fastening one (1) of the screws previously unfastened. With the SCT operations complete, the MSS was reconfigured for MLI cutting and manipulation tasks using the WCT (Figure 9).

Figure 9: WCT Cutting a Corner in the Kapton MLI

The MLI Kapton involved piercing a small hole in the Kapton blanket with the cutting spade and then cutting a 3-sided tab in the blanket. The first cut involved several attempts but was eventually successful. While starting the second cut however, the Kapton ripped and several small pieces were seen floating away. Operations were halted and the MSS was backed-off to a park configuration.

After determining it was safe to continue cutting, Day 4 of the operations continued with the cutting tasks. Eventually, three (3) cuts were achieved and the WCT was used to fold back the newly cut tab and attach it to a magnetic attachment point. The next part of the procedure was to cut a wire underneath; however, operations were running behind schedule. Therefore, this part of the procedure was omitted and the flap was reclosed so that the task-board could be removed as part of RRM Phase 2 operations. Another operation that was omitted due to time limitations was the MLI manipulation task using the WCT grippers.

4.1 Tertiary Tasks Discussion

The tertiary tasks involved very small motions, often with low load constraints that represented the very limit of the SPDM capabilities.

During the SCT operations, six (6) attempts were required to fully seat the SCT on the TSA. This was due to the fact that SPDM normally relies on FMA to correct any misalignments required to attain a perfectly aligned configuration and achieve full seat.

In this case there was a combination of initial misalignments coupled with moments that were not large enough for the SPDM to detect in order to correct the small misalignments which prevented the SCT from properly seating on the TSA. The video signal quality may also have contributed to the difficulties in alignment.

The video synch issues seen were a result of upgrades made to the ISS video systems. The RRM cameras were not included in the end-to-end (EtE) testing of the upgraded video system and used a slightly different configuration than the cameras which were tested. This issue highlights the need for EtE testing for data and video signals being transmitted over several sub-systems.

Manipulating the MLI with the tip of the WCT proved easier than expected. Cutting the MLI was a greater challenge. When cutting the MLI, the major difficulties were in trying to limit the forces to an amount slightly above the minimum limits of the SPDM capabilities, during performance of small motions while in contact with a flexible surface.

The goal was to limit the loads to prevent tearing the MLI. In addition, the motion was constrained to prevent the blade from contacting the surface below the blankets while maintaining a straight cut. This proved to be feasible but it was difficult to keep the blade from exiting the cut. It was also very easy to snag if the MLI was not kept tight.

Accurately simulating cutting the MLI in 0 Gravity (0G) prior to operations was not feasible. The data collected during these operations by the RRM team will be invaluable to planning future MLI robotic operations. As nearly all ORUs on the ISS are covered with MLI the capabilities provided by the WCT are useful not only for satellite servicing but also for ISS maintenance.

5 Acknowledgment

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All photographs used in this paper are courtesy of NASA/CSA.

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6 Conclusions

The RRM has shown that many of the tasks required for robotic on-orbit servicing of satellites is feasible with current technology. Using the RRM tools, the SPDM was able to successfully demonstrate the robotic techniques required to align the tools for successful contact operations, limit the loads using FMA and manipulate constrained payloads such as the ENT (Figure 10).

The major factor in the success of these operations was in preparing for the operations with extensive hardware testing, computer modeling and analysis performed prior to the operations by GSFC, CSA and MDA. The efforts of all team members leading up to and during the operations contributed greatly to the success of RRM.

7 References

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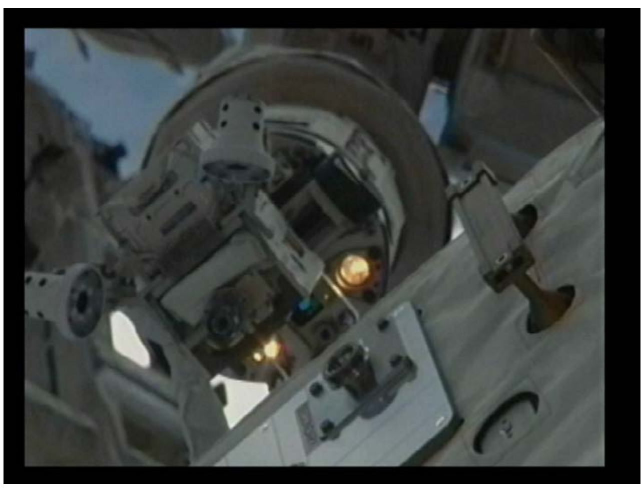

Figure 10: OTCM shown holding the ENT in an inspection position checking for FOD