Dextre Operations 2011 Milestones

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![Dextre, Canadarm2, and HTV-2 on ISS over the Gulf of St-Lawrence after successfully unloading the HTV-EP in February 2011.]

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I. Introduction

2011 has been a very busy and successful year in terms of robotics on International Space Station (ISS), with many firsts being accomplished by Dextre, the Canadian Space Agency (CSA) dexterous robot onboard. This paper describes the challenges surmounted by the CSA and MDA (MacDonald, Dettwiler and Associates the manufacturer of Dextre) engineering teams to achieve the following important milestones:

In July 2010, after the commissioning phase was completed, Dextre, commanded from the ground, attempted unsuccessfully to swap two small circuit breakers, RPCMs (Remote Power Controller Module) on the ISS. The culprit was an unexpected electromagnetic shielding that held the RPCM in place with a force higher than analyzed during mission planning.

The focus had to be re-directed on preparing for the HTV-2 (H-II Transfer Vehicle – logistic vehicle) mission scheduled for February 2011. During this mission, Dextre unloaded two spare ORUs (On-orbit Replaceable Unit) from the HTV-2 Exposed Pallet (EP) and stowed them on itself. The installation of the ORU on the temporary platform required the dexterity of Dextre and its Force and Moment Accommodation (FMA) to insert the ORU with enough precision to align the connectors.

The failed RPCM from July 2010 was removed and replaced successfully on August 29, 2011. The main hurdle was applying the appropriate extraction load to overcome the force holding the RPCM in place without exiting the worksite. With the help of FMA, the forces were kept under an acceptable level (between 29 and 35 lbf) and in the correct direction. The other concern was being able to insert the replacement RPCM.

These successes were achieved using ground commanding of the robots for numerous contact operations. It paves the way for an upcoming refueling demonstration mission on ISS and on-orbit servicing of satellites. Dextre’s primary role is to replace failed electronic boxes on the ISS, but a secondary goal is to push the boundaries of ground-operated, space-based robotics.
II. RPCM Remove & Replace

A. RPCM hardware

Following Dextre’s (SPDM – Special Purpose Dexterous Manipulator) arrival on the ISS via the Space Shuttle Endeavour (1J/A flight / STS123) in March 2008, Dextre’s first maintenance task was to swap two circuit breakers or RPCMs (Remote Power Controller Module). One RPCM controls multiple ports and numerous RPCMs are distributed inside and outside the station to control its power distribution. Failure of an RPCM port occurs quite often on the station and they need to be replaced to ensure redundancy of the power string. These maintenance operations have been performed until now by astronauts and are more problematic for RPCM located outside the ISS as it requires the crew to perform an EVA (Extra Vehicular Activity).

The interface for this small On-orbit Replaceable Unit (ORU) is not directly compatible with Dextre’s arms. Therefore, a special tool called RMCT (Robot Micro-Conical Tool) was required to ensure compatibility with the MCF (Micro-Conical Fixture) (Figure 1).

B. Commissioning and first attempt

Before using Dextre for an operational task as critical as manipulating RPCMs, a commissioning campaign in several phases was planned. In addition to testing the planned capabilities of the robot, the second purpose was to test new software functionalities for ground commanding. The updates for ground commanding were designed and uplinked after Dextre was already on orbit. Dextre was designed to be operated by the crew, but, because of the time required to perform an operation and to reduce the overhead on the crew, it was decided that Dextre would be operated exclusively from the ground. The commissioning lasted about 1 year and Dextre performed as expected. Most of the tests were successful the first time, and others required tuning of the control parameters such as the filters required on the Force and Moment Sensor (FMS), critical for good performance of the Force Moment Accommodation (FMA) algorithm.

In July 2010, after the commissioning phase was completed, the extraction of a RPCM was first attempted. The plan was to swap a failed RPCM (located in the P1 truss) with another fully functional and operational unit (located in the P3 Truss). The purpose behind the swap was that the RPCM in the P1 was using different output ports than the one on the P3 to regain all the functionality without launching a new RPCM.

To prepare this operation, the Mission Planning team at the CSA performed both dynamic analysis based on data provided by the hardware manufacturers and also hardware in the loop test with what was thought to be a flight model RPCM unit. According to the data, the force that was required to pull an RPCM outside of its worksite was approximately 22.0 – 44.5 N (5-10 lbf). However, once Dextre’s arm with the RMCT was confirmed to be in the proper configuration and started pulling with a force of 100 N (22.5 lbf), and no significant movement was seen in downlink video or telemetry, it became clear that the force required was much more than anticipated. In fact, the motion observed was mostly due to Canadarm2 (the Space Station Remote Manipulator System, or SSRMS) deflecting. This is known as phantom FOR (Frame of Resolution - 6 DOF position based on a given a reference frame) motion where it seems that the position of the payload (RPCM) is moving away from the worksite but it is actually Dextre’s base that is moving towards the worksite. This is permitted by the flexibility in Canadarm2’s joint gearboxes. After
investigating further with astronauts who had already performed an extraction manually on orbit, it was discovered that the culprit was an unexpected EMI (Electro-Magnetic Interference) spring used for shielding from Electro-Magnetic Interference (see Figure 2). The EMI springs held the RPCM in place with a force higher than analyzed during mission planning. This was confirmed by the hardware provider, realizing that the RPCMs and worksite unit used for testing on the ground did not have this shielding. Given that the extraction force required was now between 125 and 160 N (28 - 36 lbf), this caused a complication: A risk of the RPCM exiting the worksite and re-impacting it as a result of the stored energy in Canadarm2. Before re-attempting the operations it was decided that a better evaluation of the dynamics of the problem was necessary.

C. Challenge of RPCM extraction

The success of the RPCM extraction depends not only on Dextre’s capability to pull hard enough but also on the joint configuration of Canadarm2 being rigid enough. When Dextre is pulling at the required force, Canadarm2 should not deflect too much so the RPCM held by Dextre is not extracted outside the worksite. FOR should not travel more than 22.6 cm in X (see Figure 3). X cm deflection for Canadarm2 means at the release of the EMI springs the resulting motion for Dextre would be 2X (See in Figure 4 where X=9 cm, the worst case would be 2X = 18 cm).

Figure 3: FOR and interfaces

![Figure 3: FOR and interfaces](image)

Figure 4: “Phantom” FOR when extracting

![Figure 4: “Phantom” FOR when extracting](image)
Once it was realized that the force required to remove the RPCM was much higher than expected, it was obvious that the key parameter to characterize would be the extraction force required to overcome the electromagnetic shielding. To determine the force as precisely as possible, extraction tests were conducted using a Ground Testing (GT) facility with hardware in the loop: a Dextre arm with a flight-like RPCM (with the electromagnetic shielding this time!). These measurements were used to tune the simulation model and by varying the spring stiffness of the electromagnetic shielding, which acts like a spring, it was calculated that for the worst case electromagnetic shielding spring stiffness, the maximum force could be as high as 160 N (36 lbf) and the nominal was about 125 N (28 lbf). However, the dynamic simulation was also showing that 125 N (28 lbf) was the highest force that we could pull with without risking the RPCM exiting the worksite and avoid possibly re-impacting the worksite with the RPCM.

In order to make sure that 125 N was not exceeded, the use of FMA (Force Moment Accommodation) was mandatory. FMA is a control algorithm that uses sensors (called FMS – Force Moment Sensor) at the end of each Dextre arm to measure moments and forces exerted at that point in 6 Degrees of Freedom (X, Y, Z, Pitch, Yaw, Roll). FMA’s control will relieve these forces and moments by correcting the FOR command. For the specific operation of extracting an RPCM, FMA was instrumental in order to control the extraction force in the X direction to not exceed the 125 N (avoiding exiting the worksite) and also to resolve the off axis forces and moments to zero to minimize the loads sustained by the RPCM and both Dextre and Canadarm2 during the extraction (see Figure 3).

In the worst-case scenario where the extraction force would have been 160 N, a contingency technique had been put in place, called the wiggle technique. The extraction would have been performed by pulling 125 N in X, but in addition, a Pitch (around Y axis) manoeuvre would be performed (± 2 degrees with a maximum moment of 40 Nm controlled by FMA). This would have allowed overcoming a 160 N force but by only pulling in X with 125 N and so not risking exiting the worksite. It was determined by simulation that as much as 7 cycles of pull combined with positive and negative Pitch would be necessary to overcome the 160 N and it would have taken a lot of time to perform on-orbit. However, it was considered the safest way to proceed if the straight pull did not succeed.

D. On orbit execution

In August 2011, the on-orbit execution was finally scheduled. This time instead of swapping 2 RPCMs it was planned to replace the same failed RPCM from July 2010 with one stored in the CTC (Cargo Transport Carrier – a container used to carry ORUs) brought by HTV-2 in February (see section II). At the time Dextre still had the RRM (Robotic Refueling Mission) payload on one side of its a two-sided stowage platform (known as the EOTP (Enhanced On-orbit Replaceable Unit Temporary Platform see Figure 5) and was holding the CTC by one of its arms. Before the removal and replacement of the RPCM started, the CTC based on an AFRAM was stowed on the other side of the EOTP (see Figures 6 and 7). Both of Dextre’s arms were free to open the CTC lid for Dextre to access the spare RPCM and to grasp both RMCTs.

Figure 5: SPDM with EOTP
Figure 6: SPDM with both RMCTs (GMT242/2011)

Figure 7: SPDM after failed RPCM extraction
As per the nominal plan, the command was sent to extract the RPCM with a force limited by FMA to 125 N. After about 120s (60 s at maximum force), the RPCM came out of the EMI with the FMS reading 128 N. The force measured was very close to the results of the simulation. The RPCM was seen backing off around 16 cm but staying in the worksite because of the SSRMS deflection around 9 cm before the EMI force dropped. It was then very easy to extract the RPCM slowly and completely out of the worksite along the L-guide (see Figure 8).

The other arm, holding the replacement RPCM, was aligned for insertion in the now empty worksite. This was achieved quite easily with the help of the Snapshot frame taken when the failed RPCM was extracted. A snapshot frame is a feature that creates a display frame at any place the SPDM Arm FOR (Frame Of Resolution) is positioned. This Snapshot frame Display Frame can then be re-loaded to return to this exact position. FMA was activated in case it would require some alignment when moving along the L-guide, but the FMS reading during the insertion did not show significant off axis force or movement confirming that the initial alignment was quite good.

During the insertion of the new RPCM an unanticipated problem occurred. First, the force to insert the new RPCM was higher than expected (160 N), but it was not an issue because Dextre could push the circuit breaker with a much higher force than it could pull it. 160 N was still in the acceptable range according to our analysis.

The next issue was use of the “Apply Tip Force” command. The purpose of this command is to set a force to attain in a given axis. Once the software detects that the force is reached and only at this point, it will accept a fasten command for the socket on the end of Dextre’s arm. It is analogous to when fastening a screw with a screwdriver where it is required not only to turn but also to push down with a given a force, called pre-load, to be able to engage the first thread of the bolt. However in the on-orbit conditions the control software was not considering the force to be steady enough and so the fasten command could not be sent. In order to complete the task another apply tip force command of 160N was sent and once the desired force was seen (through telemetry) then the brakes were applied on all the joints of the arm. The fasten command could then be sent as the desired pre-load was achieved. The bolting was then successful, and the failed RPCM was powered back on, making the operation a success. The only task remaining was to stow the failed RPCM in the CTC. This was executed flawlessly.

E. Lessons Learned

One of the main lessons learned is how critical it is to have the correct data for analysis and to use hardware that represents actual on-orbit equipment when performing testing on the ground. Based on this lesson, after the collection of data obtained from all the stakeholders (the CSA, NASA and the hardware provider), a meeting is organized to review the data before the dynamic analysis begins. At this meeting, the data collected and the assumptions for these analyses are reviewed and approved by all the represented parties.

Otherwise, the on-orbit data collected during the removal and replacement of the RPCM allowed us to verify and tune our model for future RPCM extractions. As described above, it appears that the configuration of the joint angles of both Canadarm2 and the operating Dextre’s arms is very critical for the success of the extraction and insertion of an RPCM. The required force needed to be achieved with a reasonable deflection of Canadarm2 to avoid exiting the worksite. Other RPCMs located at the proximity of the RPCM replaced in August 2011 have been assessed and could be also R&R (Remove & Replace) as the joint angles configuration would be very similar and would be
successful. However, other RPCMs at very different locations would need specific analysis to assess the success of the mission. However, with the numerous degrees of freedom of the MSS (Mobile Servicing System) system (which is comprised of the Mobile Base System on the Mobile Transporter, Canadarm2, and Dextre), a suitable configuration can be found, to guarantee the success of any RPCM R&R. This paves the way for Dextre to be declared good for servicing the ISS and assisting with maintenance, thus reducing the number of required EVAs.
III. Unloading FRAM based ORUs

A. HTV-2 (H-II transfer Vehicle – logistic vehicle) mission
The HTV spacecraft are unpiloted Japanese vehicle launched on an H-II rocket. Once on-orbit and in proximity of the ISS, it approaches the ISS, stabilizes its position and waits to be grappled by Canadarm2. Once berthed on the Node-2’s (Harmony) CBM (Common Berthing Mechanism), Canadarm2 grapples the EP (External Pallet see Figure 9) located in the HTV’s unpressurized section. The EP, carrying the new spares (for HTV-2 the spares were FHRC – Flex Hose Rotary Coupler, a spare part for the solar arrays and CTC) is installed on the JEF (JEM (Japanese Experiment Module) Exposed Facility). This is where Dextre, riding on the end of Canadarm2, grasps the ORUs by their interfaces (see Figure 10), the FRAM (Flight Releasable Attachment Mechanism).
B. FRAM interface

The FRAM is a standard mechanism used on the Station to carry and stow ORUs (see Figure 11). The ORUs are on the active interface (AFRAM) that can be connected to any passive interface (PFRAM) on the Station such as External carriers (Express Logistics Carrier (ELC)).

C. Mission planning and re-planning

Initially, the ELC-4 (see Figure 12) (on which the FHRC and CTC would be stowed) was scheduled to be launched to the ISS on shuttle flight STS-133/ULF-5, prior to the launch of HTV-2. However, because of cracked brackets on the shuttle’s external tank delaying the launch, the plan had to be changed to be able to unstow the ORUs and keep them on Dextre until the ELC-4 could be launched. This required two additional verifications: first, that both ORUs could be powered to ensure their thermal control; and second, analysis needed to be performed in order to confirm that routine operations would not exceed the maximum loads that the MSS could handle. These routine operations included: Station reboost, visiting vehicle (Shuttle, Soyuz, Progress and Automated Transfer Vehicle-ATV) docking and undocking and attitude control manoeuvres. It was finally decided that the FHRC would be stowed on the EOTP (see Figure 5) and be powered by Dextre through the FRAM interface connectors.

The CTC was a more complex problem. Due to clearance issues, it would not be practical to stow it on the other side of the EOTP. This is the reason why one arm had to extract the CTC from the EP grasping it by the AFRAM fixture, and then, in free space, the other arm had to grasp the CTC by the Lid fixture, which has an umbilical interface and therefore is able to receive power.

D. Challenges of the Mission

1. Extraction of AFRAM on PFRAM

One of the first concerns regarding the extraction of the AFRAM from the PFRAM were the forces induced by the magnetic soft dock, which were estimated to be 80 N (18 lbf). The analysis showed that with the MSS configuration (Canadarm2 and Dextre arm joint angles) required for the HTV-2 operations and the low joint current limits imposed by proximity operations, Dextre could barely overcome the 80 N (18 lbf).

Another concern regarding the extraction force was a potential oscillation when the magnetic force drops to zero, causing a potential re-contact with the structure. The analysis using Dextre showed some oscillations causing low energy impact which was deemed acceptable. However, to prevent any re-contact, extraction with Canadarm2 was chosen as the primary method for the first on-orbit trial.

The first on-orbit AFRAM extraction performed in December 2010 demonstrated that this force was in fact around 45 N (10 lbf). The fact that the required force was much less than expected allowed Canadarm2 to extract with margins, and even Dextre could perform it. The choice of which manipulator will perform the extraction...
depends on the configuration required for the operation. Essentially, the manipulator providing the most extraction force, i.e. the manipulator that has all 3 Pitch joints aligned with the AFRAM extraction axis (-X).

At the time of writing, 3 AFRAM extractions have been performed from a non-EOTP location (2 from EP and 1 from ELC-3). All 3 were completed by pulling with Canadarm2. Three extractions were successfully performed by Dextre from the EOTP. In all 6 cases, the magnetic forces observed never exceeded 45 N (10 lbf).

2. Installation of AFRAM on PFRAM

The installation of the AFRAM on the PFRAM was another challenging task for Dextre further complicated because the interface was designed not only for robotics but also for EVA (Extra-Vehicular Activities). The geometry of the alignment guides is such that if the AFRAM is inserted parallel to the PFRAM, there is a high probability that the connector door would not be rotated and results in the AFRAM getting stuck. This would be the case if the AFRAM was biased in the –Z direction (see Figures 13, 14 and 15). That is the reason why during the installation the AFRAM has to be biased in the +Z direction. Also, to ensure that the contact between the coarse alignment guide and the pin occurs before the connector door contacts with AFRAM assembly when translating down (+X), the AFRAM is rotated (-Pitch: rotation around +Y see Fig 15) before it comes in contact with the PFRAM. Force Moment Sensor (FMS) will be the prime cue to detect contact with coarse alignment guide in Z.

Before the final single axis manoeuvre down (+X) was executed, the AFRAM needed to be rotated back in order to be parallel to the PFRAM. This is due to the limitation of single axis commands when using FMA. If the command was to be sent while the AFRAM was rotated it would result in not only motion along the installation axis (+X), but also along the axis perpendicular to it (+Z) at the same time.

Once the AFRAM is fully seated on the PFRAM, the allowed misalignment in orientation at the seated position is quite small: 0.8 degrees to be able to extend and properly mate the connectors. The success of the operations resides a lot on FMA’s capability to help the insertion by detecting contact and re-orienting the AFRAM as needed. In addition, the operator has no visual cues on the guides and can only rely on markings on the AFRAM and PFRAM which does not provide a good cue to know if the interfaces are aligned. To mitigate this lack of cues, operators use simulated views of the interfaces to compare with the actual views.

The first insertion of an AFRAM on-orbit was performed in December 2010. It involved installing a CTC based on an AFRAM on EOTP side 2. Problems occurred when the AFRAM seemed to have reached its fully seated position. After the final +X command, the brakes were applied before FMA had fully resolved all the small misalignments. The bolting of the pins and connector was completed, but only after multiple re-alignments were done to reach the fully seated position.

At the time of writing, 7 insertions have been performed on-orbit (1 on ELC-3, 3 on ELC-4, 3 on EOTP), one of which had been particularly difficult. The installation in question was when the CTC was installed on EOTP side 1.
for RPCM R&R. It required several attempts but eventually succeeded. The number of insertions performed did not allow for any conclusions on the reasons for this difficulty. The cause may have been that the site on the EOTP was used for the first time or it could have been also because of a higher stiffness of the system (Dextre without Canadarm2) compared to when Canadarm2 is in the dynamic path when installing on the station). However no evidence was found it was one of these explanations. The other installations were completed without issue either on EOTP or an ISS site (only 1 required a re-alignment on the ISS site).

3. Capture of the FRAM fixture on EP

A challenge that was discovered when performing the operation on-orbit was the difficulty to capture the AFRAM on the EP, because of the flexibility of the ISS. The flexing (caused by expansion and contraction of modules) of the ISS results in unintentional movement between Dextre’s arm tip and the alignment target on the EP. The long chain of pressurized modules (see Figure 16) between the two generates relative drift during the periods of loss of commanding capability due to loss of communications with the ISS (video KU and command S bands). The future operations planned with the EP are trying to work around this issue, especially for insertion of an item to be disposed on the EP, by stabilizing Dextre with its other arm by grasping the fixture on the EP.

![Figure 16 Dextre approaching ORUs on EP (GMT034/2011)](ISS026E024629)

E. Lessons Learned

As was the case for the RPCM, the FRAM mission preparation shows again the criticality of having the correct data at our disposition. In this case, the extraction force seen on orbit was much lower than expected and did not have an impact on the success of the mission. However, it has still to be considered in any planned FRAM extraction as a magnetic force of 80 N (18 lbf) specified by the hardware provider may still be encountered. It is the reason why, specifically for Dragon trunk FRAMs extraction and installation, PFRAM hardware modifications have been put in place to remove the metal part interacting with the AFRAM magnet and to remove the connector door. This was acceptable because Dragon trunk is not accessible to EVA and these features were designed for EVA assist and protection.

These first on-orbit experiences brought other lessons learned allowing to refine the procedures (let FMA resolve the forces even if the AFRAM seems to be at the seated position, contingency procedure for pitch and yaw moment).
Also, for future ORUs that may have to be disposed on the EP (HTV-4), consideration has been given to performing the installation of the AFRAM carrying the ORUs while stabilizing with the other arm on the EP. This is to avoid the drift observed during HTV-2 when performing the delicate manoeuvre.

Finally, after HTV-2 FRAM operations and the ones following, system parameters and procedures were developed that are generic enough to be used for any type of FRAM-based ORUs. This was a big milestone knowing that FRAMs are a very common interface on the ISS.
IV. Conclusion

2011 has seen Dextre perform successfully its first operational tasks. The criticality of these tasks made them even more a resounding success for station maintenance and re-supply. These successes are important for the ISS community to increase their confidence to extend the life of the ISS until 2020. The RPCM R&R confirms Dextre’s capability not only to replace the RPCM that may fail in the future, but also other types of ORUs. The capability of Dextre to manipulate FRAM based ORUs with a reduced level of effort in the preparation will be instrumental in the unloading of the different free flyers like HTV and Dragon that will re-supply ISS during upcoming missions.

Finally, the high level of performance demonstrated by Dextre in 2011, and more recently the very successful first phase of the Robotic Refueling Mission (RRM), is paving the way for space robotics operations that will service and extend the lifespan of satellites or support space exploration in lunar or Martian mission.
## Appendix A

### Acronym List

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<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>AFRAM</td>
<td>Active Flight Releasable Attachment Mechanism</td>
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<td>ATV</td>
<td>Automated Transfer Vehicle</td>
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<tr>
<td>CBM</td>
<td>Common Berthing Mechanism</td>
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<td>CSA</td>
<td>Canadian Space Agency</td>
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<td>CTC</td>
<td>Cargo Transport Carrier</td>
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<td>EMI</td>
<td>Electro Magnetic Interference</td>
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<td>EOTP</td>
<td>Enhanced ORU Temporary Platform</td>
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<td>EP</td>
<td>Exposed Pallet</td>
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<tr>
<td>EVA</td>
<td>Extra Vehicular Activity</td>
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<td>FHRC</td>
<td>Flex Hose Rotary Coupler</td>
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<td>FMA</td>
<td>Force and Moment Accommodation</td>
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<td>FMS</td>
<td>Force and Moment Sensor</td>
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<td>FOR</td>
<td>Frame Of Resolution</td>
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<td>FRAM</td>
<td>Flight Releasable Attachment Mechanism</td>
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<td>GT</td>
<td>Ground Testing</td>
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<td>HTV</td>
<td>H-II Transfer Vehicle</td>
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<td>JEM</td>
<td>Japanese Experiment Module</td>
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<td>JEF</td>
<td>JEM Exposed Facility</td>
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<td>MCF</td>
<td>Micro Conical Fixture</td>
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<tr>
<td>MDA</td>
<td>MacDonald, Dettwiler and Associates</td>
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<td>MMSF</td>
<td>Modified Micro Square Fixture</td>
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<td>MSF</td>
<td>Micro Square Fixture</td>
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<td>MSS</td>
<td>Mobile Servicing System</td>
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<tr>
<td>ORU</td>
<td>On-orbit Replaceable Unit</td>
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<td>PFRAM</td>
<td>Passive Flight Releasable Attachment Mechanism</td>
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<td>RMCT</td>
<td>Robot Micro Conical Tool</td>
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<td>RPCM</td>
<td>Remote Power Controller Module</td>
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<td>RRM</td>
<td>Robotic Refueling Mission</td>
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<td>SPDM</td>
<td>Special Purpose Dexterous Manipulator</td>
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<td>SSRMS</td>
<td>Space Station Remote Manipulator System</td>
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Appendix B

References

