Planning and Execution of Tele-Robotic Maintenance Operations on the ISS

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The Mobile Servicing System (MSS) is a complex robotic system used extensively in the assembly, inspection and maintenance of the International Space Station (ISS). With the ISS construction now complete, the focus of MSS operations has shifted from assembly support to external maintenance activities. In 2011, the MSS successfully completed its first two logistics and maintenance operations using the Dextre robot: the relocation of new ISS components, delivered by the Japanese H-II Transfer Vehicle, and the removal and replacement of a failed ISS power controller module. This paper describes the planning and execution of Dextre's first tele-robotic operations. It summarizes the significant technical challenges encountered and presents the operational techniques developed to overcome them. Ground-controlled operations are shown to be an effective method to maximize external maintenance capability, and therefore ISS lifetime, as well as on-orbit crew availability for science activities. It is found that components designed to be robotically-serviceable can frequently present unforeseen challenges, driving the need for flexible operational tools and techniques, such as the use of force/moment sensing and accommodation. As a result, the approach developed for Dextre lends itself readily to future ISS maintenance tasks, but also to more general robotics exploration and satellite-servicing missions.

I. Introduction

Canada's primary contribution to the International Space Station (ISS) consists of the Mobile Servicing System (MSS). The MSS includes the Space Station Remote Manipulator System (SSRMS, or Canadarm2), the Mobile Base System (MBS), and the Special Purpose Dexterous Manipulator (SPDM, or Dextre), shown in Fig. 1. The Canadarm2 is a 17m long, seven degrees-of-freedom (DOF) robotic manipulator which has been used extensively for the assembly of the ISS. The MBS is equipped with four Power Data Grapple Fixtures (PDGF), which can each be used as a base by the Canadarm2. The Canadarm2 can "walkoff" from one MBS PDGF to another, in addition to two other PDGFs located on the ISS Destiny (Lab) and Harmony (Node 2) modules. Attached to the US-built Mobile Transporter (MT), the MBS can be relocated to any one of eight pre-defined locations along the ISS truss (worksites 1 to 8), thereby extending the effective MSS reach. Dextre is designed to be operated as a dexterous extension of the Canadarm2 for ISS maintenance. Astronauts can control the MSS from two redundant Robotics Workstations (RWS) on the ISS. The MSS has also been increasingly commanded directly from ground workstations located at the Johnson Space Center's (JSC) Mission Control Center Houston (MCC-H), and from the Canadian Space Agency's (CSA) mission control facility in St-Hubert, Canada.

With the ISS construction now complete, the focus of MSS operations has shifted from assembly support to resupply and maintenance activities. In September 2009, ISS astronauts used the Canadarm2 to catch the first ISS free-flyer.[1] It is anticipated that the MSS will be required to capture, offload, and release up to six unmanned resupply vehicles per year. The continued need to use the MSS for ISS maintenance was also vividly illustrated in August 2010 when a critical cooling pump located outside of the ISS pressurized volume failed. The Canadarm2 was used extensively over the course of three Extra-Vehicular Activities (EVA) to assist the astronauts in the

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replacement of the failed component.[2] It should be noted that ISS systems include hundreds of such external electronics components, intended to be replaceable on-orbit. Approximately 250 of these On-orbit Replaceable Units (ORU) were designed to be replaced by Dextre in an effort to reduce the projected EVA workload.

Dextre began supporting logistics and maintenance operations in late 2010. First, it demonstrated its capability to transfer a spare ORU from one ISS location to another. It was then tasked with the stowage of new ISS spare parts, delivered by the HTV-2 resupply capsule, on an ISS external stowage platform. Later that year, Dextre replaced a faulty Remote Power Controller Module (RPCM) with a spare unit. This paper summarizes these first on-orbit tele-robotic operations and shares the technical challenges encountered during the planning and execution of these tasks. It begins with a brief description of Dextre's architecture, before presenting the current operational philosophy. The paper then describes the planning and execution of typical Dextre on-orbit activities, drawing examples from the HTV-2 transfer and RPCM replacement operations. The paper concludes with a discussion on how the lessons learned over the past year of Dextre operations can be applied to future ISS maintenance tasks, but also to more general robotic exploration and satellite-servicing missions.

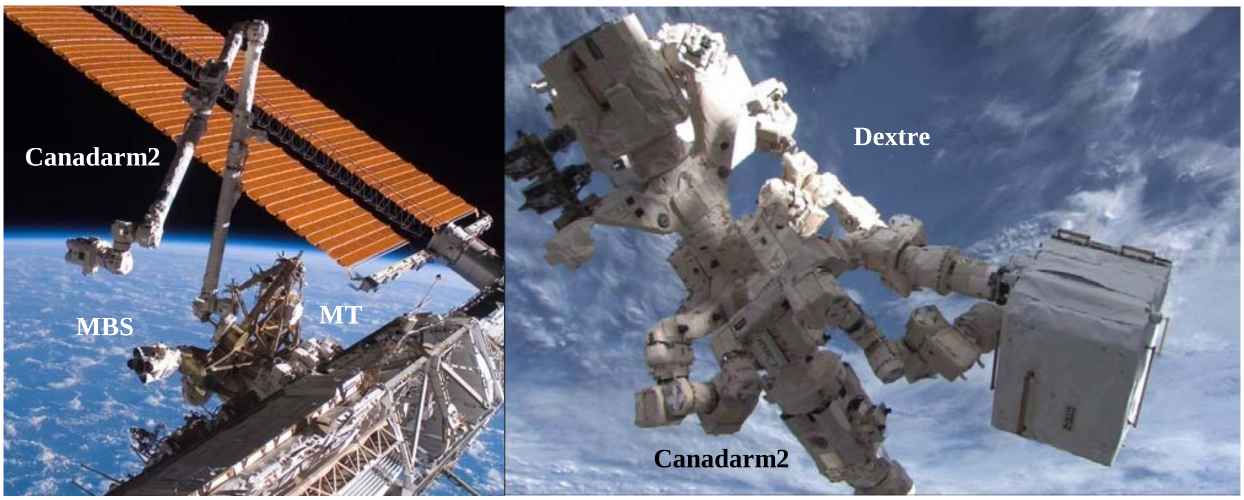

Figure 1. The Mobile Servicing System

II. Dextre Overview

Dextre, shown in Fig. 2, is comprised of upper and lower body structures. The upper body includes a PDGF, avionics platforms, as well as two identical seven DOF arms. The PDGF allows Dextre to be operated at the end of the Canadarm2, as shown in Fig. 1. Dextre's lower body consists of a Latching End Effector (LEE), a Tool Holder Assembly (THA), two cameras, and a 3-sided Enhanced ORU Temporary Platform (EOTP). Multiple ORUs can be temporarily stowed on the EOTP, which can be rotated by Dextre's arms to facilitate ORU access. Dextre's LEE is a grappling effector, similar to the ones on the Canadarm2, which allows Dextre to be based on an ISS or MBS PDGF when not operated at the end of the Canadarm2. The upper and lower body structures are connected via a Body Roll Joint (BRJ). The BRJ allows Dextre's arms to reach the THA and EOTP by rotating the upper body structure relative to the lower one.

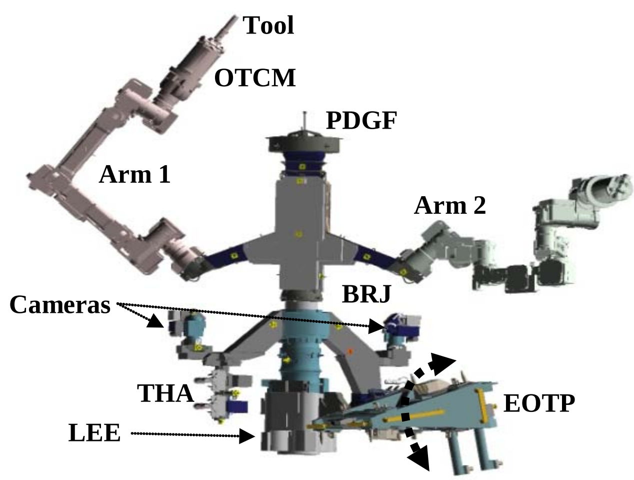

Figure 2. Dextre Components

Each of the two 3.5-m long arms is comprised of seven revolute joints and an ORU/Tool Changeout Mechanism (OTCM). The OTCM (Fig. 3) uses grippers to mechanically grasp specially designed fixtures on the ISS and robotically-compatible ORUs (Fig. 4). There are six different types of grasp fixtures and six different types of targets in use on the ISS. Once grasped to a fixture, the OTCM's 7/16" drive socket, located between its grippers, can be extended to engage bolts located in the center of the fixtures. These bolts actuate mechanisms which fasten (or unfasten) an ORU to its receptacle, or which mate (or demate) its electrical connectors. In addition to its gripping and bolt-driving capabilities, each OTCM is equipped with power/data/video umbilicals for communicating with and/or powering attached payloads. Finally, OTCMs include a bore-sight camera designed to align the OTCM with a grasp fixture using its associated target. Dextre is also equipped with three different types of tools, which can each be grasped and actuated by an OTCM. These tools allow Dextre to interface with fixtures and bolts not designed to be handled directly by an OTCM. When not in use, the tools are stowed in the THA.

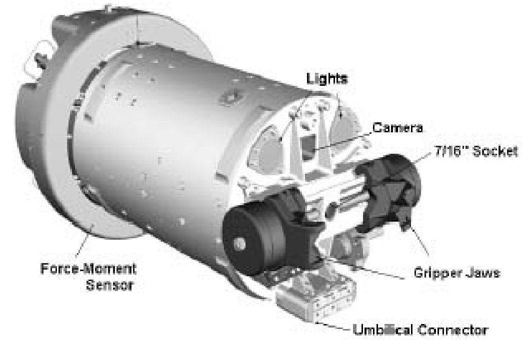

Figure 3. ORU/Tool Changeout Mechanism

Because of the delicate nature of its insertion tasks, Dextre relies on a Force-Moment Sensor (FMS), located at the back of each OTCM, for force control. FMS measurements are used by a Force-Moment Accommodation (FMA) control algorithm, which simplifies the alignment process and limits the forces and moments exerted on ORUs (and their surroundings) during their insertion.

III. Dextre Operational Philosophy

A. Evolution of Dextre's Operations Concept

Early Canadarm2 operations relied extensively on Human-In-the-Loop (HIL) modes of operation, in which operators on the ISS use hand-controllers to maneuver the manipulator. However, it was quickly revealed that the use of operator-commanded auto-sequences, where an operator specifies the desired final manipulator configuration, either as a set of target joint angles or as the desired position/orientation of the payload, could considerably streamline robotic operations as opposed to HIL modes.

As further experience was gained with the Canadarm2, concerns were raised that the duration of complex Dextre maintenance operations would not meet ISS astronaut workday constraints, which is normally limited to 6.5 hours, or would exceed maximum unpowered periods for ORUs. A 2002 CSA-NASA Technical Interchange Meeting (TIM) proposed three key solutions to mitigate these concerns:‡

1. The development of a ground control capability that would allow for the more mundane portions of robotic maintenance to be performed and monitored from the ground .
2. The replacement of the original ORU Temporary Platform (OTP) with an Enhanced OTP, providing multiple storage areas for ORUs as well as the ability to provide power to their heater circuits. The EOTP would not only simplify the operational sequences, but also allow them to be broken up into smaller segments which could be scheduled over longer periods. As a result, Dextre's OTP was replaced with the EOTP in 2010.
3. The development of a Cargo Transport Container (CTC), a box containing smaller ORUs and compatible with Dextre's EOTP and OTCM, which could provide thermal conditioning to the replacement units during maintenance operations (Fig. 4).

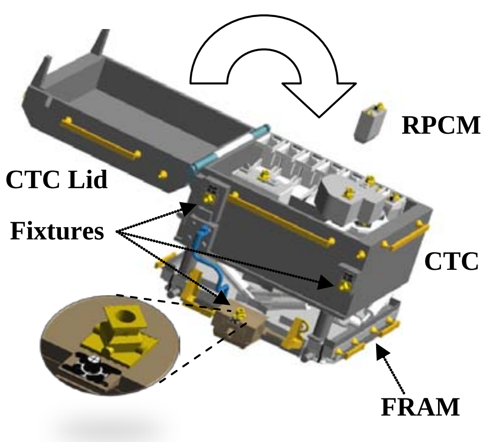

Figure 4. Dextre-Compatible Cargo Transport Container and Flight Releaseable Attach Mechanism

Following this TIM, a limited ground control capability was first introduced for the Canadarm2 in 2005. Until then, ground commanding had been limited to MSS activation, diagnostics, and camera surveys. The ability to safely perform small maneuvers in free-space was demonstrated first, and this capability progressively grew to

‡Special Purpose Dexterous Manipulator Task Timeline TIM, Johnson Space Center, Houston, August 6-8, 2002.

include coordinated joint motion without any restriction on maneuver size. When Dextre arrived on orbit in 2008, a large proportion of Canadarm2 maneuvers were operator-commanded auto-sequences initiated from the ground. Consequently, it was proposed that Dextre's on-orbit checkout and commissioning activities be designed as a demonstration and validation of its ground-based tele-robotics concept of operation. The commissioning process spanned nearly two years, and involved progressively more complex demonstrations of free-space maneuvering, OTCM functionality, fine-alignment tasks, and contact operations involving Dextre's tools.[3] Hence, all Dextre operations discussed in this paper were controlled entirely from the ground.

B. Mission Planning

The replacement of an ISS component by Dextre involves a complex, meticulously-choreographed series of robotics operations. Typical removal and replacement operations begin with the retrieval of Dextre from its stowage location, which can be one of several MBS or ISS PDGFs, by the Canadarm2. The desired spare is then retrieved from one of the Station's External Stowage Platforms (ESP) or Express Logistics Carriers (ELC) (Fig. 5). Spare units covered in this paper were either contained in a CTC or integrated directly onto a Flight Releasable Attach Mechanism (FRAM). A FRAM, shown on Fig. 4, is a type of ORU carrier compatible with Dextre's OTCM and EOTP. The failed component is then replaced in situ with the spare unit. The operation concludes with the return of the failed component to a suitable storage area, which typically corresponds to the initial location of the spare unit. Dextre must then be stowed on the ISS to allow the Canadarm2 to support other robotics objectives. For all operations, the MT/MBS and Canadarm2 must bring Dextre in the vicinity of the desired worksites (i.e. the stowage area for the spare unit and location of the failed component.)

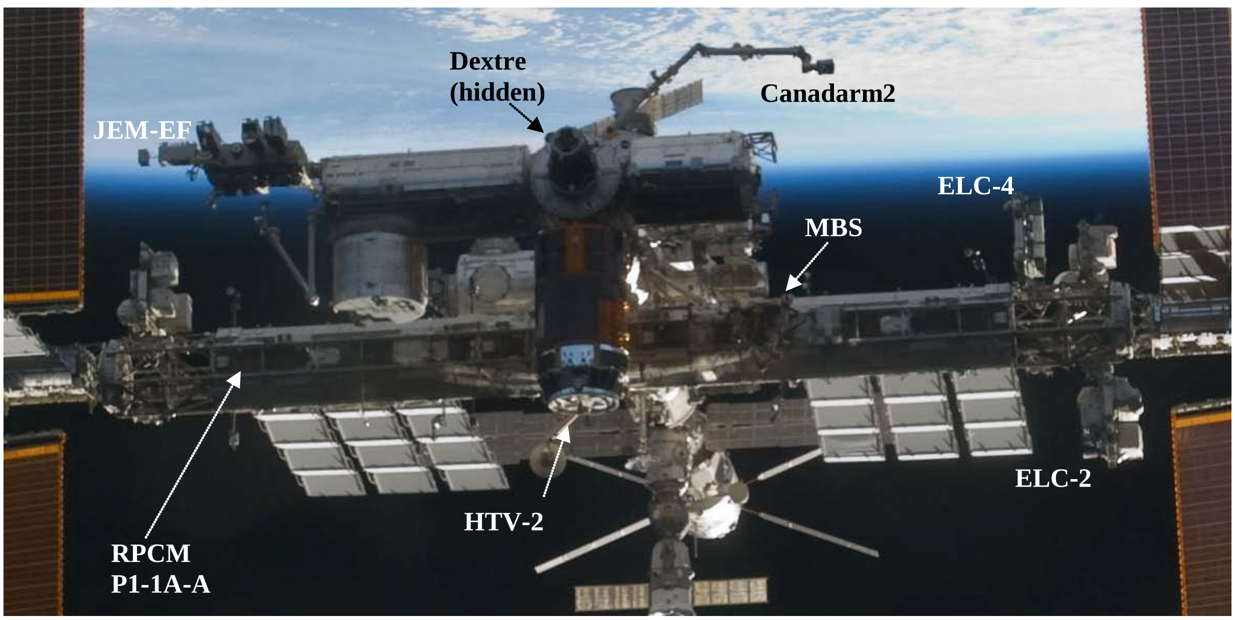

Figure 5. Dextre Work Areas on ISS for 2011

MSS mission planning can be summarized by the following six major aspects: (1) trajectory design; (2) procedure development and validation; (3) command script development and certification; (4) generation of task-specific software configuration files; (5) dynamic and thermal analyses; and (6) integration into ISS activities.

Once an MSS logistics or maintenance operation has been identified, Canadarm2 and Dextre trajectories are designed using the Robotics Planning System (RPS). The RPS is a kinematic graphics simulator which replicates the external ISS environment, as well as the motion of the Canadarm2 and Dextre, with a high-degree of fidelity (Fig. 6). Mission designers use this tool to divide the trajectory into a series of auto-sequences and verify that the resulting operational sequence meets its intended objective, while remaining clear of singularities, self-collisions, joint limits, and structural clearance concerns.

Mission designers then specify the desired auto-sequences and MSS commands into a specialized syntax made of keywords, each specifying a particular MSS function or control feature. This customized language is used by an automated procedure generation tool to produce the required operational procedures and command scripts.[3] The procedures, developed in MS Word format, are used as the primary document for the review, approval, and execution of the operation by the flight control team. The command scripts generated are text files used by MCC command applications to implement the directives listed in the procedures.

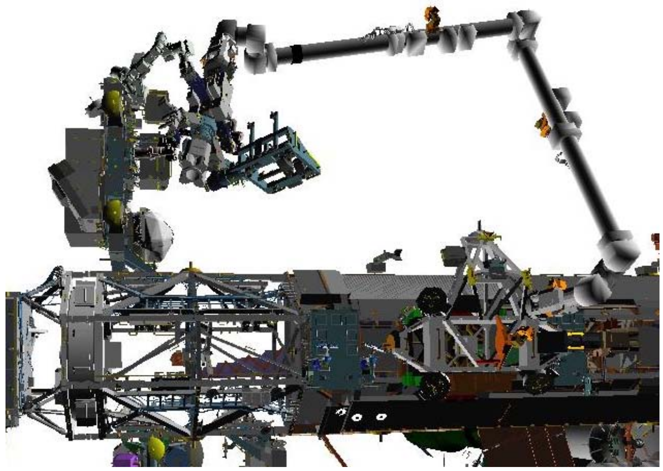

Figure 6. RPS Graphics Simulation of FRAM Relocation Demonstration

Once generated, procedures are subject to a careful independent validation process involving multiple flight controllers using both simulator validation and desktop reviews. This process ensures that the procedures meet all documented constraints, standards, and flight rules. This includes ensuring continuity from one procedure to the next; that no maneuver exceeds maximum travel constraints; that clearance concerns are properly identified and mitigated; that the MSS will not interfere with the operation of external ISS systems or payloads; and that documented system behaviour, previous flight history and anomalies have been suitably addressed. In parallel, flight controllers also verify the predicted maneuver durations and resulting communication link requirements. They also perform command script certification, to ensure that the script accurately reflects the procedure directives.

Dextre's performance must also be optimized for each specific task through the use of customized thresholds, gains, and limits contained in software parameter files. Since FMA plays a critical role throughout Dextre's contact operations, extensive dynamic analyses are carried out prior to each operation. Thermal analysis is also required to establish how much time an ORU can remain unpowered during transfer operations before it reaches its lower temperature limit.

Procedures must be completed and validated one week prior to the scheduled start of the operations to allow their integration into the overall ISS plan. MSS activities are highly interdependent with several other ISS systems. For instance, a failed component must be electrically isolated from its own system before Dextre can remove it. In addition, several robotically-serviceable ORUs are located in the vicinity of articulated structures such as solar arrays and radiators. These must locked in position before the MSS enters the area of concern to ensure that safe clearances are maintained. The extensive use of FMA, in addition to the desired positional accuracy (of the order of a few mm), requires ISS thrusters to be inhibited during contact operations. Even the small accelerations generated by some astronaut exercises may affect MSS operations and must be constrained. Use of video downlink channels, the selection of suitable telemetry formats, and the availability of relay satellite coverage must also be negotiated with other flight control disciplines.

Finally, contingency procedures and analyses must be developed in order to return the ISS to a safe configuration and recover all required functionality in the presence of an ISS or MSS anomaly. These include Canadarm2 procedures to extract Dextre from its worksite following a failure; use of Dextre's backup drive unit to complete an ORU insertion or extraction; and Crew procedures to recover from an ISS loss of attitude control.

C. Mission Execution

Every on-orbit MSS operation is supported by a team of three robotics flight controllers (the "ROBO" team). The lead flight controller sits in the primary ISS flight control room in MCC-H, and is assisted by two other flight controllers who are located in separate rooms ("backrooms"), either in MCC-H or at CSA. All MT relocations, Canadarm2 and Dextre operations described in this paper were controlled entirely by this team from the ground.

Ground-controlled MSS operations typically begin with the MSS activation, which can take up to 90 minutes. A video survey of the ISS exterior follows, using MSS and ISS cameras, which is downlinked to the ground. The survey covers the entire space the Canadarm2 and Dextre are expected to traverse and verifies there are no clearance concerns. The primary objective is to confirm that the ISS configuration along the planned trajectory matches the RPS models used to develop and validate the procedures. The survey is also required to protect for the possibility of loss of video downlink during ground-controlled MSS motion, thereby affecting the ability of the ground operators to monitor clearances.

The MSS ground control protocol is a methodical, highly structured and scripted commanding sequence that requires two flight controllers to execute any command. During execution, the procedures are followed by all team members to ensure that the correct step of the correct procedure is being executed. For each step in the procedure, the team agrees on the step to be executed, confirms that the system is in the expected configuration, and verifies there is adequate communication coverage for the command execution. Prior to each command uplink, the lead flight controller and one other agree on the command to be uplinked. The command is then uplinked to the ISS and the team monitors its execution. Initiating Canadarm2 or Dextre joint motion requires the uplink of three successive commands (using the above process) in a "Ready-Arm-Fire" protocol. It should be noted that the MSS software only allows one of its manipulators to be in motion at any given time. Here, the “Ready” command corresponds to loading the desired kinematic configuration, the “Arm” command confirms the desired configuration, and the “Fire” command initiates motion. Prior to uplinking the “Load” command, both the commander and verifier are required to verify that the contents of the command (destinations) match the procedure being executed. Once motion is initiated, the ROBO team monitors the Canadarm2/Dextre trajectory and clearances using downlinked views (when available), telemetry displays, and telemetry-driven RPS models. If unexpected motion is observed, the lead flight controller issues a single “Safing” command to arrest motion.

IV. FRAM Relocation Demonstration (December 2010)

Dextre’s commissioning was scheduled to be concluded in July 2010, when it would carry out the complete replacement a partially-failed RPCM. Aside from commissioning considerations, the primary objective of this operation was to swap two operational RPCMs. The “RPCM swap” would place the inoperative output channel of the failed RPCM in an unused location at the other RPCM’s location, thereby regaining full functionality on both RPCMs. Dextre performance was nominal, but it was not able to extract the RPCM from its worksite, despite pulling with the maximum force rated for this ORU (100 N). It was noted that each unsuccessful attempt to remove the RPCM resulted in significant Canadarm2 deflections. Although Dextre could have applied a higher pull force (up to 200 N), concerns that the resulting Canadarm2 oscillations could cause the RPCM to re-contact the ISS once it broke free prevented further attempts. Further ground analysis isolated the issue to an unexpected mechanical interference from the RPCM’s electro-magnetic shielding. The RPCM swap was deferred to allow the determination of a valid higher pull force, and the generation of procedures to safely extract the RPCM.

The additional analysis and potential operational concept modification required to complete the RPCM replacement drove the decision to shift the focus to the preparation of the upcoming HTV-2 ORU transfer, which was deemed a higher priority. In its unpressurized section, the HTV-2 was bringing a new Flex Hose Rotary Coupler (FHRC), to be used as a spare for the station’s external thermal control system, and CTC-2, which carried spare RPCMs and an MSS Video Distribution Unit (VDU). Since both the CTC-2 and FHRC were installed onto a FRAM, Dextre was assigned the task to transfer these ORUs to ELC-4 (Fig. 5). In order to ensure readiness for the HTV-2 mission and verify Dextre’s ability to overcome the FRAM’s magnetic soft-dock force (estimated to be 80N), it was decided to perform a FRAM extraction and insertion prior to the mission. This “FRAM Relocation” would use Dextre to relocate CTC-3 from Site 1 to Site 2 on ELC-2 (Fig. 7). As a secondary objective, the EOTP’s FRAM mechanical and electrical interfaces would also be verified by temporarily stowing CTC-3 on the EOTP before its final installation to Site 2. Although the CTC-3 relocation would improve EVA access to the CTC’s contents, its success was not critical to ISS operations, making this particular task well-suited for such a demonstration.

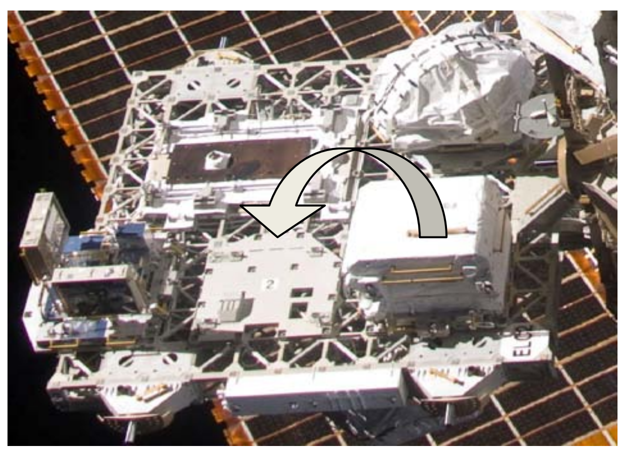
Figure 7. CTC-3 Relocation on ELC-2

The FRAM relocation took place over 6 days, from December 20, 2010 to January 4, 2011. The Canadarm2 was first walked from Node 2 over to the MBS, before retrieving Dextre which had been stowed on the Lab PDGF. The MT then relocated the entire MSS to the vicinity of ELC-2. Once maneuvered into position by the Canadarm2, Dextre removed CTC-3 from ELC-2 Site 1, before placing it on the EOTP. The next day, CTC-3 was removed from the EOTP and installed on ELC-2 Site 2. The operation concluded when Dextre was put down on MBS PDGF2 and the MSS was translated back towards the center of the Station's main truss. Table 1 shows the detailed sequence of events associated with this operation. The times for each subtask are also shown in hours and minutes to illustrate typical activity durations.

Table 1. FRAM Relocation Operational Sequence

Day	Major Activity	Detailed Activities	H:MM
Dec. 20	**MT Relocation**	MT is translated from Worksite 3 to 5.	3:35
	Canadarm2 "Walkoff" from Node2 PDGF to MBS PDGF3	MSS activation and pre-motion survey.	1:00
		Canadarm2 maneuvers to grapple MBS PDGF3.	1:45
		Canadarm2 grapples MBS PDGF3, changes its base, before releasing Node 2 PDGF.	0:55
		Canadarm2 reconfiguration.	0:50
Dec. 21	**Dextre Relocation from Lab PDGF to Canadarm2 and Reconfiguration for Translation**	MSS activation and pre-motion survey.	1:00
		Canadarm2 maneuvers to grapple Dextre.	0:50
		Canadarm2 grapples Dextre, Dextre changes its base to the Canadarm2, before releasing the Lab PDGF.	2:05
		Canadarm2 and Dextre reconfiguration.	2:30
	MT Relocation	MT is translated from Worksites 5 to 2.	3:15
Dec. 22	**CTC-3 Extraction from ELC-2 (Site 1) and Installation on EOTP**	MSS activation and pre-motion survey.	2:00
		Dextre reconfiguration (BRJ and Arm1).	0:20
		Canadarm2 moves Dextre into position near ELC-2 Site 1.	0:25
		Dextre Arm 1 moves in to grasp CTC-3 FRAM fixture.	0:25
		Arm 1 alignment and final maneuver for grasping.	0:50
		Arm 1 grasps FRAM fixture and unfastens FRAM from ELC-2.	0:40
		Canadarm2 maneuvers Dextre and CTC-3 FRAM away from ELC-2.	1:00
		Dextre BRJ rotation to permit EOTP access.	0:10
		Dextre Arm1 maneuvers CTC-3 FRAM over EOTP Side 2.	1:05
		CTC-3 FRAM alignment, insertion, and fastening onto EOTP using Arm 1 (4 attempts were required).	4:40
		Canadarm2 maneuvers to overnight configuration.	0:30
Dec. 23	**CTC-3 Removal from EOTP, Installation on ELC-2 (Site 2), and Canadarm2/ Dextre Post-Activity Reconfiguration**	MSS activation and pre-motion survey.	1:00
		Dextre Arm 1 releases CTC-3 FRAM from EOTP.	0:25
		Dextre Arm 1 extracts CTC-3 FRAM from EOTP.	0:45
		Dextre BRJ rotation to move EOTP clear of the worksite.	0:10
		Canadarm2 maneuvers Dextre into position near ELC-2 Site 2.	0:30
		Dextre Arm 1 positions FRAM for alignment maneuvers.	0:15
		CTC-3 FRAM alignment/insertion attempts without FMA.	2:30
		CTC-3 FRAM alignment/insertion with FMA, and fastening onto ELC-2 (Site 2).	0:50
		Dextre Arm 1 releases the FRAM microfixture.	0:02
		Dextre Arm 1 maneuvers away from CTC-3.	0:10
		Canadarm2 reconfiguration.	1:00
		Dextre arm reconfiguration for stow.	0:30
Jan. 3	**MT Relocation**	MT Translation from Worksites 2 to 5.	4:00
Jan. 4	**Dextre Stowage on MBS PDGF2**	MSS activation and pre-motion survey.	1:30
		Canadarm2 maneuvers Dextre to grapple MBS PDGF2.	0:55
		Dextre grapples MBS PDGF2, Dextre base change, Canadarm2 releases Dextre.	0:40
		Canadarm2 reconfiguration.	0:30

The successful relocation of CTC-3 from one storage site to another was representative of many of Dextre's future tasks. Although the Canadarm2 had been previously used to maneuver Dextre from one area of the ISS to another, this was the first end-to-end Dextre task involving complex contact operations and the extensive use of FMA. The FRAM relocation not only validated Dextre's concept of operation and completed its on-orbit commissioning, but also led to the following observations.

Despite concerns that the required extraction force would exceed robotics requirements (and potentially cause the Canadarm2/Dextre to bounce back towards structure), no such issues were associated with the extraction from either ELC-2 or the EOTP. In both cases, the OTCM demated successfully the FRAM connector with the nominal torque, and the Canadarm2 pulled Dextre holding CTC-3 smoothly. The FRAM's magnetic soft dock forces remained below 27 N as the Canadarm2 began motion approximately three seconds after the command was sent.

The insertion maneuver on the EOTP was performed using FMA. During the final insertion maneuver, ground operators concluded that the maneuver had completed and issued a command to terminate the motion. Although real-time FMS readings and the absence of motion on the video downlink seemed to confirm the completion of the maneuver, post-operation analysis revealed that FMA was still working at reducing the moment in the Yaw axis at that time, which was still relatively high. The premature interruption prevented the FMA from fully seating the interface and resulted in the need to perform several additional alignment corrections. The insertion challenges were compounded by a temporary loss of FMS data, which caused the insertion to be completed without FMA. The FMS issue was induced when power was deliberately removed from Dextre's lower body in order to safely mate the FRAM electrical connectors to the EOTP power distribution system. Overall, it was concluded that future final insertion maneuvers must be allowed to run for a longer duration to give FMA the opportunity to completely correct misalignments. In addition, future FRAM attachments to the EOTP should be performed as a two-stage operation, during which power to the SPDM lower body would only be removed once the FRAM is structurally attached to the EOTP, but before electric connectors are mated. This would prevent any loss of FMS data.

The insertion maneuver on ELC-2 was first attempted without using FMA in order to demonstrate the feasibility of a non-FMA installation in the event of a failure of the FMS. Despite several attempts, it was not possible to complete the installation without FMA. Timeline constraints prompted the operators to revert to an FMA approach. Capitalizing on the previous day's experience, FMA was given a longer time to relieve loads at the interface and successfully complete the installation. It was concluded that installation without FMA is a "best effort" approach and can require considerable additional time to accomplish.

Finally, scheduling this operation proved to be surprisingly difficult because of the frequently changing launch date of the STS-133 mission, resulting in conflicting configuration requirements for MT and Canadarm2 support. In addition, the timing of MT translations was also made difficult by the requirement to have an EVA capability (which is not available throughout the year due to ISS crew rotations) to protect for stranded MT contingencies requiring EVA support.

V. HTV-2 ORU Transfer (February 2011)

Dextre's first official mission consisted of unloading two newly-delivered ORUs, a spare FHRC and CTC-2, from the HTV-2's Exposed Pallet (EP). The HTV-2 was launched from Japan on January 22, 2011 and rendezvoused with the ISS five days later. ISS astronauts used the Canadarm2 to capture the vehicle and berth it to the Station. The following day, the astronauts commanded the Canadarm2 to remove the EP from the HTV-2's external cargo trunk and hand it over to the Japanese Experiment Module's (JEM) robotic arm, which then attached it onto the JEM Exposed Facility (JEM-EF), seen in Fig. 5. Both the FHRC and CTC-2 were integrated onto FRAMs, themselves securely fastened to the EP. The extraction of both ORUs followed a sequence similar to the one presented in Table 1. Dextre Arm 1 was used to transfer the FHRC from the EP to its EOTP, where power could be provided to the FHRC heating circuits. Dextre Arm2 then extracted CTC-2, handling it by the FRAM fixture, while Arm1 grasped another fixture directly on the

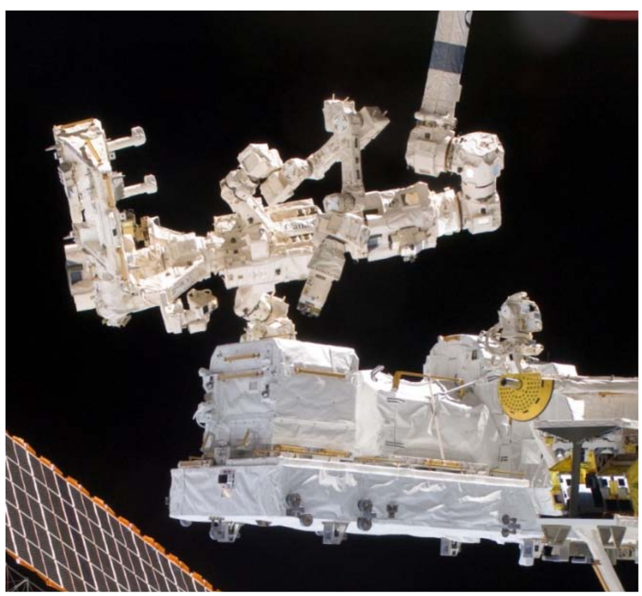

Figure 8. FHRC Extraction from EP

CTC lid, through which power could be provided for thermal regulation. The FHRC would remain on EOTP Side 2, while the CTC-2 would be held at the end of SPDM Arm1 until the arrival of ELC-4, scheduled for the following month.

The approach previously developed for the FRAM relocation was used: Canadarm2 maneuvers were used to remove both the FHRC and CTC from the EP once they had been grasped and unfastened by Dextre's arms (Fig. 8). Again, the extraction was executed smoothly for both ORUs. Applying lessons learned from the December FRAM Relocation, the FHRC installation on the EOTP was completed more efficiently by letting FMA operate longer until all loads had been relieved, and by completing the FRAM's mechanical engagement before powering down Dextre's lower body.

Nevertheless, unanticipated difficulties arose when grasping the FRAMs for both the FHRC and CTC: The ROBO team was surprised to discover that the OTCM had drifted by approximately 7 cm relative to the micro-fixture after standing down for a planned 30 minute communication outage (Fig. 9). This drift was later attributed to the length of the kinematic chain between Dextre's OTCM and payloads attached at the end of the JEM-EF. The chain was highly susceptible to the relative motion of the Station's modules and structures induced by the orbital environment. However, the experience from the FRAM demonstration had led the ROBO team to schedule additional shifts of longer durations to account for such unexpected issues.

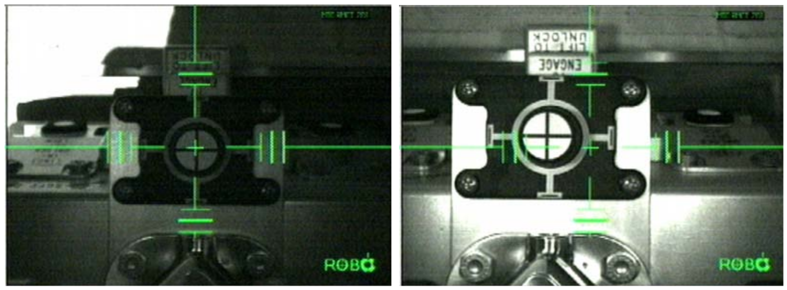

Figure 9. OTCM Drift During Communication Outage

VI. RPCM P1-1A-A Removal and Replacement (August 2011)

In August 2011, the focus for Dextre operations shifted back towards the removal and replacement (R&R) of RPCM P1-1A-A, which had been unsuccessfully attempted the previous year. The plan was revised to replace the failed RPCM with a new spare unit contained in CTC-2, instead of swapping it with another RPCM currently in operation. Additional analysis had been performed over the previous year to ascertain the highest force Dextre could apply to safely extract the RPCM from its enclosure. Several options were considered to overcome the high extraction force, but the final decision was to have Dextre's arm pull with a force of 125 N for several minutes, relying on FMA to control the magnitude of the applied force and minimize any misalignment. Ground analysis and hardware tests had indicated that this force was likely to free the RPCM, without completely extracting it from its alignment guides, thus ensuring that the Canadarm2 deflection would not cause the RPCM to escape the worksite and hit the ISS. An alternate technique, combining straight pulls with small positive and negative pitch adjustments was also developed as a backup method for extraction.

Figure 10. Dextre Opening CTC-2 Lid.

Many aspects from the RPCM R&R differed from previous FRAM transfers. Firstly, RPCM's are equipped with micro-conical fixtures, which are not designed to be grasped directly by an OTCM. This meant that both of Dextre's Robotics Micro-Conical Tools (RMCT) would be used to grasp and actuate the RPCMs fixtures and co-located bolts. Secondly, this maintenance operation would mark the first time that Dextre would actuate a CTC mechanism to unlatch, open and close its lid (Fig. 10). And thirdly, this would be the first time that two payloads would be placed simultaneously on the EOTP: Astronauts had installed the Robotics Refuelling Mission (RRM) demonstration module onto Dextre's EOTP (on the now vacant Side 2, since the FHRC had previously been installed on ELC-4 in April 2011) during an EVA on the final Space Shuttle mission in July 2011. The RPCM R&R

called for CTC-2 to be installed on the EOTP as well. This would require an EOTP rotation to install CTC-2 onto EOTP Side 1. Table 2 summarizes the main execution steps associated with the RPCM R&R.

Table 2. RPCM R&R Operational Sequence

Day	Major Activity	Detailed Activities
	Initial Configuration	MT/MBS located at Worksite 6, near location of failed RPCM P1-1A-A. Canadarm2 based on MBS PDGF3. Dextre located at the tip of the Canadarm2, holding CTC-2 at the end of Arm1, and supporting the RRM module on EOTP Side 2.
Aug. 1-Aug. 2	**CTC-2 Stowage on EOTP**	Dextre Arm 2 rotates the EOTP 120° clockwise to facilitate the installation of CTC-2 on EOTP Side 1.
		Dextre Arm2 grasps the CTC-2 FRAM fixture.
		Arm 1 releases the CTC-2 lid fixture.
		Arm2 installs CTC-2 on EOTP Side1 (multiple attempts over two days).
Aug. 10	**Tool Unstow and CTC Lid Checkout**	Arm2 grasps and unstows RMCT2 from the THA.
		Arm1 grasps the CTC-2 lid latch fixture, actuates the mechanism to unlatch the CTC lid, and releases the latch fixture.
		Arm1 grasps the CTC-2 lid hinge fixture, and actuates the mechanism to fully open and close the CTC lid.
Aug. 28	**RPCM R&R Day 1**	Arm1 actuates the mechanism to fully open the CTC-2 lid and releases its fixture.
		Arm1 grasps and unstows RMCT1 from the THA.
		Arm2 grasps the spare RPCM's fixture in CTC-2 and engages its collocated bolt.
Aug. 29	**RPCM R&R Day 2**	Arm2 unfastens the spare RPCM and extracts it from the CTC.
		Arm1 captures the RPCM P1-1A-A fixture.
		Failed RPCM P1-1A-A is first powered down, before Arm1 unfastens and extracts the RPCM from its site.
		Arm2 inserts and fastens the spare RPCM in the P1-1A-A site, before the new RPCM P1-1A-A is powered up. Arm2 then releases the RPCM.
		Arm1 inserts and fastens the failed RPCM into the CTC.
Aug. 30	**RPCM R&R Day 3**	Arm1 releases the failed RPCM and stows RMCT1 back in the THA.
		Arm1 grasps, and closes the CTC-2 lid, before releasing it and maneuvering clear.
		Canadarm2 and Dextre are reconfigured for translation.

The RPCM extraction out of the P1-1A-1 from its site was successful on the first pull, with a maximum force of 128 N (Fig. 11). The dynamic response of the on-orbit system matched well that predicted by ground analyses: After 60 s at the maximum force, the RPCM broke free, but did not escape its receptacle on the ISS. However, the elastic energy stored in the Canadarm2 deflection did cause the RPCM to bounce back within its alignment guide in an over-damped fashion. The insertion of the new RPCM into the P11A-A site was successful on the first attempt as well. The RPCM insertion proceeded smoothly, requiring a 160 N push force to overcome initial worksite resistance. However, maintaining the required preload during the RPCM fastening proved difficult. Four unsuccessful attempts to bolt the new RPCM were required before Dextre's brakes were applied to maintain an adequate preload on the bolt during its initial thread engagement. Bolting was then completed nominally. The insertion of the failed RPCM into the CTC was completed without any issues. Actuation of the CTC lid was also performed without any problems.

Figure 11. Dextre Extracting Failed RPCM from P1-1A-A Site

In the days following the RPCM R&R, the CTC-2 and RRM module were both removed from Dextre's EOTP and installed on ELC-4 Sites 1 and 3, respectively. Since then, Dextre's activities have been primarily directed towards supporting the Robotics Refueling Mission (RRM). The RRM is a joint NASA-CSA collaboration aimed at demonstrating that robots such as Dextre can successfully repair and refuel existing satellites utilizing specialized tools. The RRM module provides Dextre with tools and test beds, allowing the robot to cut safety tethers and thermal blankets, remove caps, and install a refuelling nozzle.

VII. Key Lessons Learned

The transfer of several FRAM-based ORUs and the RPCM replacement clearly demonstrated that complex on-orbit robotic operations could be controlled safely and successfully from the ground. Ground operators were able to perform the required fine alignment maneuvers and corrections using available system telemetry and downlinked video views; to recover from various system anomalies, unmodelled dynamics and thermal effects; and to adapt to changing plans, conflicting requirements and unforeseen circumstances. On-orbit RRM tests in early 2012 have also shown that Dextre's operational concept could be readily applied to tasks involving payloads not designed to be handled robotically.

Table 3 gives the time required to secure each FRAM to its mating interface, from an initial hover position, for all FRAM insertions which took place from December 2010 to September 2011. Although improving tools and operational techniques have reduced insertion times to approximately one hour, these times were found to vary significantly for different mating interfaces. For instance, the August 2011 FRAM insertion onto EOTP side 1 was surprisingly difficult, requiring a total of 7 hours and 35 minutes over two days of operations. Pre-operation analyses of this case had not identified any issues and Dextre's performance was nominal. Although a root cause was not determined, it was suggested that manufacturing variations of the tight clearance between the fine alignment features might have been a contributing factor. Both of the following FRAM insertions in September 2011 were completed without any issues using the same approach, suggesting that the issue may be interface-specific. Nevertheless, use of FMA was found to considerably facilitate insertion tasks in all cases.

Table 3. FRAM Interface Alignment Effort

FRAM Insertions	Duration (H:MM)
CTC-3 on EOTP Side 2 (Dec. 2010)	4:40
CTC-3 on ELC-2 (Dec. 2010) - Without FMA (with FMA)	2:30 (0:50)
FHRC on EOTP Side 2 (Feb. 2011)	1:04
FHRC on ELC-4 (Apr. 2011)	2:05
CTC-2 on EOTP Side 1 (Aug. 2011) - 1st Day (2nd Day)	5:05 (2:30)
CTC-2 on ELC-4 (Sept. 2011)	0:58
RRM on ELC-4 (Sept. 2011)	1:05

The ability to continuously improve the on-orbit software played an important role in the success of ground control. Key features required for ground-controlled contact operations were designed and uplinked after Dextre had been launched. In early 2012, Dextre's performance was further enhanced with the ability to automatically transition from a positioning control mode to a force control mode upon detection of applied forces or moments. This will remove the need for operators to stop and manually transitions from one control mode to the other while approaching the worksite for future operations.

Ground control of the MSS has resulted in considerable savings in ISS Crew time. For instance, the RRM module transfer from the Space Shuttle's payload bay to Dextre's EOTP by EVA monopolized four astronauts (two Canadarm2 operators and two spacewalkers) for one hour and 10 minutes each. Although ground-controlled MSS operations for similar tasks can take significantly longer, they offer the net advantage of not requiring any astronaut time. They also optimize the use of ISS consumables by reducing the number of required EVAs. This explains why the reliance on ground control has increased tremendously since this capability was first commissioned for the Canadarm2 in 2005. In 2011, the proportion of MSS Stage operations (operations taking place between Space Shuttle visits) controlled from the ground reached 80%.

Use of the EOTP allowed large-scale logistics and maintenance operations to be broken up into smaller phases which could be executed over a longer period of time. For instance, CTC-2 was temporarily stowed on Dextre for more than six months, whereas the FHRC and RRM both remained on the EOTP for approximately one month. This would not have been possible with Dextre's original OTP, since all three payloads required thermal regulation. The segmenting of MSS tasks increased operational flexibility by allowing Dextre to support multiple concurrent objectives and permitted operations to fit within reasonable flight control shifts. The EOTP's capability to support multiple payloads simultaneously was also found to simplify operational sequences significantly, as was the case for the RPCM R&R.

The processes and tools employed to plan tele-robotic operations must be flexible to account for replanning challenges. The delay of Space Shuttle mission STS-133 prevented the complete transfer of the HTV-2 ORUs to their final destination on ELC-4 and resulted in significant work to re-design Dextre's operations. A single day of ORU transfer necessitated the generation and validation of hundreds of procedure pages and the uplink of a correspondingly large number of commands. This prompted the ROBO team to automate the initial development of flight procedures and command scripts. Such an automated product development tool, using consistent and validated procedure templates, not only increases the efficiency of the development of an operation, but also reduces the likelihood of an error during the generation of long procedures. Efforts are currently underway to further automate both the generation and execution of MSS procedures, with the ultimate goal of having the ground operator simply monitor the execution, ready to take action if required. In addition, the experience gathered from the on-orbit activities discussed here have led to the development of new ground commanding tools, such as a "software hand controller" application, designed to facilitate alignment corrections, and tools aimed at streamlining OTCM and RMCT operations.

Finally, the generation, certification, and delivery of Dextre software parameter updates in the presence of quickly evolving requirements, together with the challenges of attempting to simulate ill-defined dynamic conditions, were also found to be one of the key areas affecting the planning and scheduling of Dextre operations.

VIII. Conclusion

MSS ground-controlled operations were used to successfully complete three logistics and maintenance robotics tasks on the ISS: (1) relocating a CTC from one ISS location to another; (2) offloading spare parts delivered by the HTV-2; and (3) replacing a failed RPCM. Through these examples, this paper demonstrated that ground-controlled robotic systems could successfully perform complex tasks on-orbit, which involved the extensive use of robotics tools, the actuation of several mechanisms, as well as the extraction from and insertion into intricate worksites. These representative tasks have also demonstrated the benefits of using ground-controlled tele-robotic operations to optimize the use of ISS resources. These benefits will become even more pronounced with the decision to extend ISS operations until 2020 and the corresponding increase in maintenance requirements. Efforts are currently underway to ensure that all required mission planning products will be in place to face this unprecedented challenge.

Approximately 250 ISS ORUs were originally deemed to be robotically-compatible. However, several of these do not completely meet all requirements for robotic-serviceability. Nevertheless, Dextre will frequently be solicited to attempt their replacement should they fail, regardless of their robotics limitations. For instance, the ISS Program enquired in November 2011 whether Dextre could be used to replace a suspect Main Bus Switching Unit (MBSU), despite the presence of thermal blankets obstructing the spare's fixtures. Dextre's ability to interact with components which are themselves not designed to be handled robotically will be an accurate demonstration of tele-robotic capabilities for satellite servicing. Since most existing satellites were launched without any consideration for on-orbit servicing, it will be important to demonstrate the robotics capability to capture, maintain, refuel, and release these satellites in order to extend their useful life. Dextre's early successes to date show that its technology and operational concept are well suited to satellite servicing and exploration applications beyond Low Earth Orbit.

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