CANADIAN SPACE ROBOTICS IN 2016: AN OVERVIEW OF RECENT AND ON-GOING ACTIVITIES

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ABSTRACT

This paper presents advances in Canadian space robotics activities that were accomplished since the last overview paper presented at the i-SAIRAS 2014 conference.

Different application areas are targeted to maintain Canada's role is space robotics. These include traditional orbital robotics applications such as the provision of space manipulators and related technologies for next-generation space stations and on-orbit servicing, as well as emerging application areas for Canada such as planetary robotics. Technologies include manipulators, rovers, robotic tools and vision systems.

1 INTRODUCTION

Canadian space robotics is approaching a cross-road, the International Space Station program has been extended until 2024 but it will clearly be sunset before the end of the 2020 decade. A few missions making use of Canadian space robotics technologies are currently under development but little is in the books for the future.

On-going space missions include the Mobile Servicing System on the International Space Station, active vision systems for on-orbit inspection and orbital rendezvous maneuvers, as well as contributions to planetary missions.

In preparation for the future, several studies and technology development activities are in progress to ensure that Canada will maintain its role in space robotics. Targeted application areas include orbital robotics applications such as the provision of space manipulators and related technologies in support of human spaceflight and on-orbit servicing. Emerging application areas such as planetary rovers and manipulators, vision systems, low power avionics and tools are also under development.

2 ORBITAL ROBOTICS

Orbital robotics is the field for which Canada is best known. Activities started in the 1970's with the provision of the Shuttle Remote Manipulator Systems (a.k.a Canadarm) to NASA's space shuttle program [1]. Since then Canada has also provided robotic elements to the International Space Station and occasional on-orbit servicing missions.

2.1. International Space Station

Canada's flagship space robotics program, the Mobile Servicing System (MSS) on the International Space Station (ISS) has been on-going since the launch of Canadarm-2 in 2001. With the extension of the ISS program to 2024, the lifetime of the MSS will be extended to 23 years, which goes beyond the original expectations when the system was built. Year after year, the MSS is used routinely to conduct maintenance operations on the ISS and to capture incoming vehicles. Over the last four years, the MSS has seen, on average, more than 650 hours of operation per year.

These hours of operation have started to take their toll on the MSS: Canadarm-2's Latching End-Effector (LEE) was recently showing signs of wear. The mechanism was requiring more current than usual to latch and the trend was showing signs that the system might be reaching its end of life soon. On-orbit lubrication seems to have solved the problem and the system is now back to near-nominal conditions.

Similarly, the MSS cameras are also reaching the end of their expected lifetime: some have started to produce hazy images. Spare cameras are being produced using more recent technologies while respecting the original interface requirements to ensure ease of replacement.

In addition to routine maintenance of the MSS, new capabilities are being developed: the MSS Application Computer (MAC) project plans to make use of existing Artificial Vision Unit (AVU) computer that has been sitting idle on ISS for several years to implement novel capabilities. These new capabilities will aim at streamlining MSS operations and pave the way for next generation robotic systems to be used on eventual future stations such as the one being planned in cis-lunar space. Capabilities to be implemented

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include features such as scripting of common operation sequences and overlays for operator assistance during the capture of incoming vehicles. Today nearly 100% of the ISS robotic operations are controlled remotely from the ground. While robotic ground control has reduced demands on the on-orbit crew, significant effort is currently still required to conduct operations; for example in 2015, approximately 53,000 robotic commands were sent to the ISS to conduct robotic operations. By automating sequences of MSS operational steps and, having them scripted and executed on-orbit via the MAC, MSS operational efficiencies will be achieved with reduced mission timelines and operator burden. The final goal is to eventually conduct sophisticated autonomous operations including free space motion, contact motion and free-flyer capture.

A second innovative project being developed for the ISS is the Dextre Deployable Vision System (DDVS), a dual-purpose active vision system that will be capable of inspecting the ISS for damage and performing relative navigation for incoming vehicles. The configuration currently under development is derived from the successful TriDAR sensor. It uses a combination of sensors to cover a broad spectrum of specifications in terms of range, resolution and accuracy. *Figure **1*** shows an artist's concept of the DDVS being manipulated by the Dextre robot.

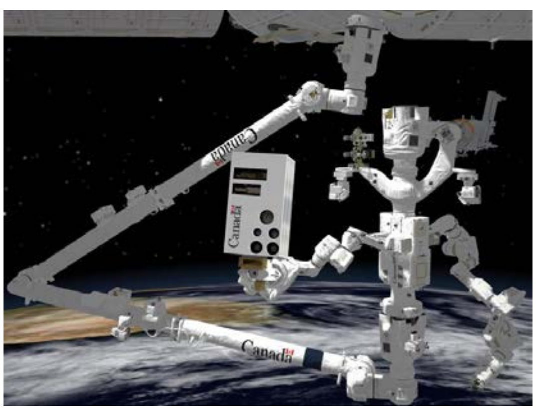

Figure 1 - DDVS sensor at the tip of Dextre

The DDVS sensor package will be used for micrometeorite damage inspection. In that mode, it uses a fine resolution LIDAR sensor with a range of 1-2 meters and a sub-mm resolution, as well as a Long-Wave Infrared camera and a near-field visible spectrum camera that will detect 1mm-sized damage at 1m stand-off distance.

It will also be used to demonstrate relative navigation capability in support of orbital rendezvous operations. In that mode, the system will be able to provide range information from 1km to 100m, and full 6 degree-of-freedom (DOF) information from 100m to 2m at a rate of 4Hz. The system is designed to function with uncooperative targets (unmarked, no retro-reflectors), using only geometry information. In relative navigation mode, the long-range LIDAR sensor has a range of 2m to 1km and a rated accuracy (both in range and lateral) of 10mm at 10 meter range. It also uses a far-field camera to complement the LIDAR information.

The DDVS sensor is designed for a five-year operational life and it will connect to the ISS WiFi networking infrastructure. Its planned launch date is 2020.

2.2. Human Space Flight Beyond LEO

One of the natural avenues for the evolution of the robotic capabilities developed on the ISS is their use in support of eventual human spaceflight programs beyond low-Earth orbit (LEO).

To investigate the feasibility and cost of participating to a "Beyond-LEO" exploration program, concept studies have just been started. Two of these studies will focus on robotic technologies for use on a cis-lunar space station: a deep-space exploration robotic system similar to the Canadarm family of robotic manipulator, and a relative navigation sensor.

These systems would be installed on a cis-lunar habitat planned for the 2020's timeframe. Some of the new challenges with this application are the need to survive 10 years and provide mission-critical service in a radiation environment much more hostile than LEO. In addition, since the cis-lunar habitat will only be manned on a part-time basis, these systems will be operated remotely most of the time and may even need to operate semi-autonomously given the round-trip communication time delays between Earth and cis-lunar space.

2.3. On-Orbit Servicing

A second avenue for the evolution or re-use of Canada's space robotics capabilities is on-orbit servicing and de-orbiting of space debris.

In that spirit, ESA has recently conducted studies to develop mission concepts to deorbit Envisat: one of the largest Earth observation satellites ever built. Envisat has operated for several years until communications with it were lost in 2012. Envisat now orbits in an uncontrolled manner in sun-synchronous orbit at an altitude of 785km. This is a very crowded orbit and Envisat is one of the largest orbital debris threats in Low Earth Orbit (LEO). It is considered a security and liability risk from both an on-orbit collision perspective and from

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an earth debris re-entry perspective.

Canada's contribution to that ESA study focused on the development of robotic solutions to capture and rigidize Envisat in order to either deorbit it or bring it to a harmless graveyard orbit.

3 PLANETARY ROBOTICS

In addition to its traditional role in orbital robotics, Canada is working towards the migration of its space robotics capabilities to other application areas. One of the most promising areas is planetary robotics where some of the know-how developed in past programs could be adapted.

3.1. Mars

At the moment, Canada's only active system on Mars is the Alpha Particle X-Ray Spectrometer (APXS) mounted at the end of the arm of the Curiosity rover. It has been operating since its arrival to Gale Crater in August 2012 and is currently in extended operations.

However, robotic components are now being designed and manufactured in Canada for ESA's ExoMars 2018 rover mission. Indeed ExoMars' Bogie Electro-Mechanical Assembly (BEMA) and Actuator Drive Electronics (ADE) are currently being built by MacDonald Dettwiler and Associates and the ExoMars Rover Navigation and Localization Cameras are being produced by the Neptec Design Group.

The BEMA system includes a three-bogie suspension design, the wheel actuators, gearboxes and the wheels themselves [2]. The BEMA program is near the end of Phase C with ongoing testing of development models at the assembly and subassembly levels. Procurement of parts for the qualification and flight models and subassembly qualification has been started.

The ADE program is currently in Phase C with development hardware and software complete and testing ongoing. Integrated testing between the BEMA and ADE development models has also commenced and will continue through first part of 2016.

For the ExoMars cameras, breadboard and engineering models have been built and subjected to environmental testing (EMI/EMC, Vibration and Shock, Thermal and Cryogenic) at unit level, and radiation testing and dust testing at sub-system level.

In preparation for future missions, the CSA has been conducting analogue missions using elements from its fleet of rover prototypes on which a rich variety of instruments and payloads have been mounted. See *Figure **2***. The most recent campaign was run in November 2015 in the desert of Utah. This mission was run under realistic conditions with an engineering team located in a control room at CSA's headquarters and a science team located at the University of Western Ontario. Neither the science team, nor the engineering team had ever seen the terrain where the rover started its mission. During the 14-day mission, the rover traversed 234 meters, acquired four samples (regolith and sedimentary material), it took microscopic images at every sample location, and acquired several images and 3D LIDAR scans of the site. In addition, X-Ray fluorescence, Raman spectroscopy and X-Ray diffraction measurements were taken from hand-held instruments throughout the mission. More details about this analogue mission can be found in [3].

Figure 2 - MESR rover deploying mini-corer and TEMMI microscope using robotic arm during the 2015 Utah analogue mission

To control the rover during the Utah 2015 analogue mission, CSA developed a rover control station based on the Apogy software suite. Apogy is a multi-mission operations and planning software framework. It is model-based and can easily be adapted to control different kinds of systems operating in different environments. It provides tools for preparing operation sequences, receiving and processing telemetry and visualizing the system and its environment.

Apogy was recently released as open-source and is now available for external use (https://bitbucket.org/apogy/ca.gc.asc_csa.apogy). It will be used to plan operations for the GHGSat nanosatellite to be launched in the spring of 2016 [4].

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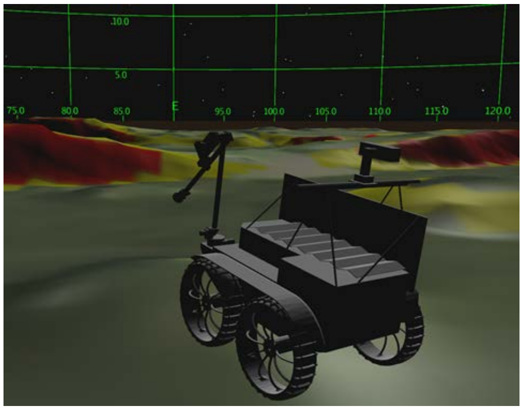

Figure 3 - Snapshot of Apogy Control Station

In order to increase the fidelity of its Mars analogue missions, the CSA has also been actively working at characterizing and maturing its rover Guidance, Navigation & Control (GN&C) technologies. Two projects involving different GN&C systems deployed onto different rovers have been conducted in parallel. One team (led by Neptec Design Group) worked on the Artemis Jr rover and another team (led by MDA) worked on the Lunar Exploration Light Rover (LELR). These projects were broken down in a sequence of four phases in which the systems were first tested under normalized conditions, then upgraded to enhance performance and reliability.

Figure 4 Artemis Jr rover (top) and LELR (bottom) during GN&C Testing

In the third phase, the characterization tests were repeated with the upgraded software. Finally, in phase 4, the systems were tested in a rock quarry that remained unknown to the teams prior to the testing. The test plan supporting Phase 4 was composed of a list of 18 waypoints that the rovers had to autonomously reach in sequence.

Phase 4 has revealed similar performance from the two systems. In both cases, the rover has traveled about 3 km in autonomous mode featuring an average relative localization error in the order of 2% of the distance traveled. Figure 4 shows the two rovers during Phase 4.

The next step in the path-to-flight for rover guidance, navigation and control software is to ensure that it can run on low-power processors. To that effect, CSA has started the Embedded Visual Odometry (EVO) project. The purpose of EVO is to port computation-intensive visual odometry algorithms to Field-Programmable Gate Arrays (FPGA) using a hybrid approach making use of logic and traditional processing. The final solution will integrate readings from inertial measurement units, sun sensors, wheel odometry, camera imagery, and possibly star trackers to provide rover localization in a lightweight (<850g) and low-power (< 8 Watts) package. The system is built around Xiphos Technologies' proven Q7 processor board [5]. The target is to obtain localization accuracy on the order of 1% and a computation speed similar or superior to modern desktop computers.

3.2. Moon

Canada's other important target for planetary robotics is the Moon. To that effect, CSA is participating in ESA's HERACLES study to define the architecture for the next human missions to the lunar surface. In the context of an eventual return of humans to the Moon, ESA is leading the definition of precursor missions and related activities leading to surface human missions. CSA actively participated to the HERACLES study that focuses on one to two rovers over 2-3 years to bring back Moon samples to a cis-lunar orbiting station for delivery an analysis on Earth. The initial phase of the study was completed in 2015 and the following phases are currently focusing on HERACLES and other precursor missions to lunar landed crew missions by 2030. CSA's focus has been to contribute inputs on the rover and its sub-systems including robotics arm.

In preparation for an eventual participation of Canada to future lunar missions, several technology development projects are being

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conducted to advance the technology readiness in several areas. The strawman mission concepts used to develop the requirements for these projects include the HERACLES architecture described above as well as NASA's Resource Prospector Mission concept.

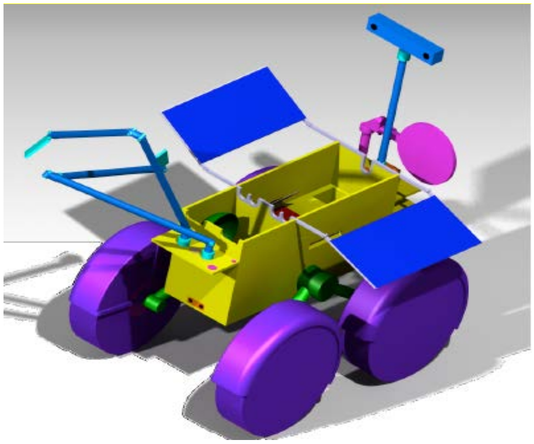

Figure 5 - Preliminary HERACLES Rover Concept

In order to address some of the highest risks that had been identified for lunar rovers, the CSA is leading technology development activities.

One major area of technology development is the capability to operate the rover in permanently shadowed areas and survive the lunar night. The default approach to this has been the usage of radioactive technologies (RHU, RTG, as part of the LPRNSS study CSA has investigated alternate technologies and approaches focusing on low temperature electronics and batteries. This study is currently being followed by a prototyping contract (RNEST) that focuses on building a representative thermal management system and testing it to demonstrate feasibility of using non-nuclear alternative technologies.

Another key related area is the Lunar Rover Platform and Drivetrain Prototype (LRPDP): a TRL-6 prototype derived from the CSA's Artemis Jr platform tested under lunar-representative environmental conditions. The LRPDP rover has a 1.6m x 1.6m chassis with a mass of 120kg and a payload capacity of 160kg. All sensitive components such as motors, gearboxes, and avionics are located in sealed compartments for thermal control and dust contamination protection. Its drivetrain was tested in CHENOBI regolith simulant at temperatures ranging from -70C to +130C. Under worst conditions, the drivetrain was exposed to temperatures of -180C for survival testing. Most of the drivetrain survived successfully 20 days of testing but issues were encountered with the actuator and an alternative solution is currently under development. *Figure **6*** shows the LRPDP drive train and test rig.

Figure 6 - LRPDP Test rig used for sprinkling regolith simulant over drivetrain

A related rover platform has also been developed: the Small Planetary Rover Prototype (SPRP): a TRL-4 functional rover prototype whose purpose is to investigate low-cost approaches to lunar exploration. At 1.2m x 1.2m and a mass of 95kg, it is smaller than the LRPDP, yet it uses the same drivetrain technology to ensure portability of the TRL-6 solution. However, the SPRP is designed with large wheels and a lockable suspension to enable mobility testing under different configurations to investigate the performance limits of suspension-less designs. *Figure **7*** shows the LRPDP and SPRP rovers side-by-side.

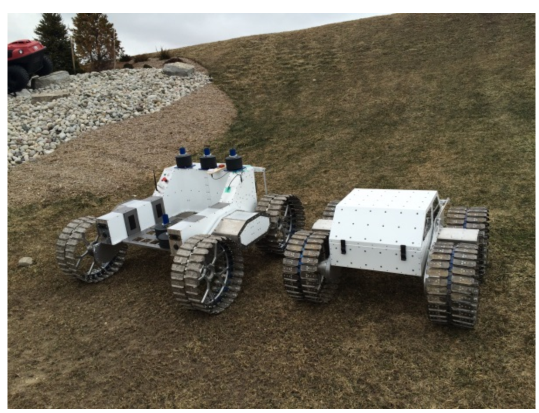

Figure 7 - LRPDP (left) and SPRP (right) rovers

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Finally, a vacuum-compatible drill unit was tested under representative lunar environmental conditions. Three different tools, namely a 50cm auger, a 1m coring auger and a 1m push tube, were used sequentially to drill under vacuum conditions (10^{-6} torr) in frozen (-110°C and below) CHENOBI lunar simulant containing 2% (4 holes) and 5% (5 holes) moisture. While the walls of the test chamber were kept around -170°C during the tests, the VDCU thermal management strategy provided heaters to maintain its operating temperature above -50°C. Coloured simulant layers were used to demonstrate that the stratigraphy was preserved in the core samples.

Prior to the thermo-vacuum test campaign, commissioning and characterization tests of the drill at ambient pressure was done for various moisture concentrations of CHENOBI regolith (0%, 2%, 5%, 7.5% and 100%) in both ambient and frozen conditions. Overall, the VDCU cumulated 50 drill holes, summing up to more than 26 meters of drilling operation (three tools combined).

3.3. Asteroids

The last class of planetary mission targets of interest to Canada at the moment is asteroids. Canada is contributing a LASER altimeter to NASA's OSIRIS-Rex mission, scheduled for launch in September 2016. The spacecraft will reach the Bennu asteroid in 2018 and return a pristine sample to Earth in 2023. The OSIRIS-REx Laser Altimeter (OLA) is a scanning time-of-flight LIDAR consisting of two lasers (one for short and one for long range) coupled to a 2-axis scanning mirror to scan across the asteroid's surface.

OLA will provide both initial high accuracy range data of Bennu for the purposes of navigation, and later complete scans of the asteroid surface to generate high density Bennu maps of the surface, specifically slopes and elevations. This data is used for selection of candidate Touch-And-Go (TAG) sites; planning the final TAG maneuver; and providing context for samples collected at the TAG sample location on Bennu.

OLA was delivered in November 2015 and was subsequently mounted onto the spacecraft. Since integration, it has been subjected to a series of system level tests and has performed flawlessly throughout. Ongoing scientific support includes simulation of expected OLA datasets for producing the shape models required by the mission and coordinating observations with other instrument teams. [6]

4 COMMERCIAL SPIN-OFFS

Interesting benefits of Canada's investments in space robotics are the commercial sales and spin-offs (both in space and on Earth) that have resulted from the re-use of the technology.

For example, has flown TriDAR rendezvous sensors on the last three launches of Orbital's Cygnus resupply vehicle [7]. The design is based on the three test missions that were performed on the STS-128, 131 and 135 shuttle flights [8]. This kind of commercial sale is a direct benefit from previous CSA investments.

Similarly, Neptec has produced a series of LIDAR sensors for industrial applications: the OPAL sensor series which includes the OPAL-360, OPAL 120 and OPAL ECR sensors, which are direct derivatives of the prototypes developed for the Canadian Space Agency [9].

Similar technology transfers are also present for robotic manipulators. For example, MacDonald Dettwiler and Associates is transferring some of the know-how acquired through space applications to the medical domain. The Image-Guided Autonomous Robot (IGAR) is being used in clinical trials by Dr. Mehran Anvari at the Centre of Surgical Invention and Innovation to perform biopsies and ablate tissue in cases of breast cancer [10]. MDA is also working with Synaptive Medical on a camera positioning robot to be used by surgeons in operating rooms. MDA is also transferring some of the technologies for 3D imaging and autonomous vehicle guidance to mining applications.

Finally, Ontario Drive and Gear, the designers of the Juno and Artemis families of rovers are now commercializing the J5 amphibious rover for a broad variety of applications ranging from military/surveillance, agriculture, research and fire-fighting.

5 CONCLUSION

With the Mobile Servicing System on the International Space Station and active contributions to orbital and planetary missions, Canadian space robotics is still vibrant. However, the probable sunset of the ISS program in the 2020 decade requires careful preparation of the future through the development of concepts and the maturation of technologies for future applications.

Different application areas are targeted to maintain Canada's role is space robotics. These include traditional orbital robotics applications such as the provision of space manipulators and related technologies for next-generation space stations and on-orbit servicing, as well as emerging application

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areas for Canada such as planetary robotics. Technologies include manipulators, rovers, robotic tools and vision systems

This paper presented a snapshot of recent Canadian space robotics activities conducted in the last two years.

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