An Overview of the Canadian Space Agency's Recent Space Robotics Activities

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Abstract

This paper provides an overview of the Canadian Space Agency's recent developments in space robotics and their relations to the CSA Exploration Program's most recent mission roadmaps. The roadmap is structured by destination ranging from LEO missions focusing on the usage of the International Space Station, to Lunar, Near-Earth Objects and Mars missions. For each activity thrust, the paper describes recent and on-going robotics developments of the Canadian Space Agency. These activities span the entire space from concept studies, prototype development, field-trials, all the way to space missions and commercialization.

1 Introduction

Space robotics is one of the four key industrial capabilities identified by Canada in its space program. The robotic elements of the International Space Station, and formerly on the US Space Shuttles, are the flagship of the Canadian space program. Canada's contribution to these programs has opened the door to Canadian astronaut flights on the Shuttle and the ISS, and has helped forge the identity of the Canadian space program.

In 2009, the government of Canada has injected significant funding in an economic stimulus program to reduce the impact of the recession on the Canadian space industry. This allowed the Canadian Space Agency (CSA) to increase funding in technology development for future space exploration missions by $110M from 2009 to 2012. Most of this additional funding was directed towards space robotics and related technologies.

The economic stimulus funds have now reached their sunset: prototypes of several crucial technologies have been designed and built. The focus is now turning to the use of these prototypes in the context of field trials and analogue missions to increase the science and operational readiness in preparation for future missions.

In parallel, on-going developments are now focusing on further advancing the maturity of selected systems and sub-systems, increasing their Technology Readiness Level in view of specific mission opportunities.

This paper provides an overview of the Canadian Space Agency's recent developments in space robotics and their relations to the CSA Exploration Program's most recent mission roadmaps. Activities are presented by destination, starting from activities in Low Earth Orbit, the Moon, Deep Space/Near Earth Asteroids, and finally Mars.

2 Roadmap of Future Space Robotics Missions

Figure 1 shows the current mission roadmap of exploration missions being considered by the Canadian Space Agency. The roadmap is structured by destination ranging from LEO missions focusing on the usage of the International Space Station to space astronomy missions exploring beyond the solar system. For space robotics, all destinations are currently being targeted except space astronomy.

The proximal portion of the time scale is populated with well-defined mission opportunities that have specific objectives and approved budgets. Logos identify the primary sponsor of each mission opportunity. Maple leafs are used to identify confirmed Canadian participations in missions.

Towards the distal end of the time scale, missions are rather grouped by theme. Canadian flags in the roadmap identify targeted long-term Canadian roles in future missions.

2.1 International Space Station and On-Orbit Servicing

The Low Earth Orbit portion of the mission roadmap focuses on the usage of the International Space Station. Since the roadmap contains only missions opportunities that would be sponsored by the Canadian Space Agency, it does not include any on-orbit servicing (OOS) mission opportunities, be they commercial, military or through industrial participation to foreign missions.

However, OOS technologies are still of interest to the

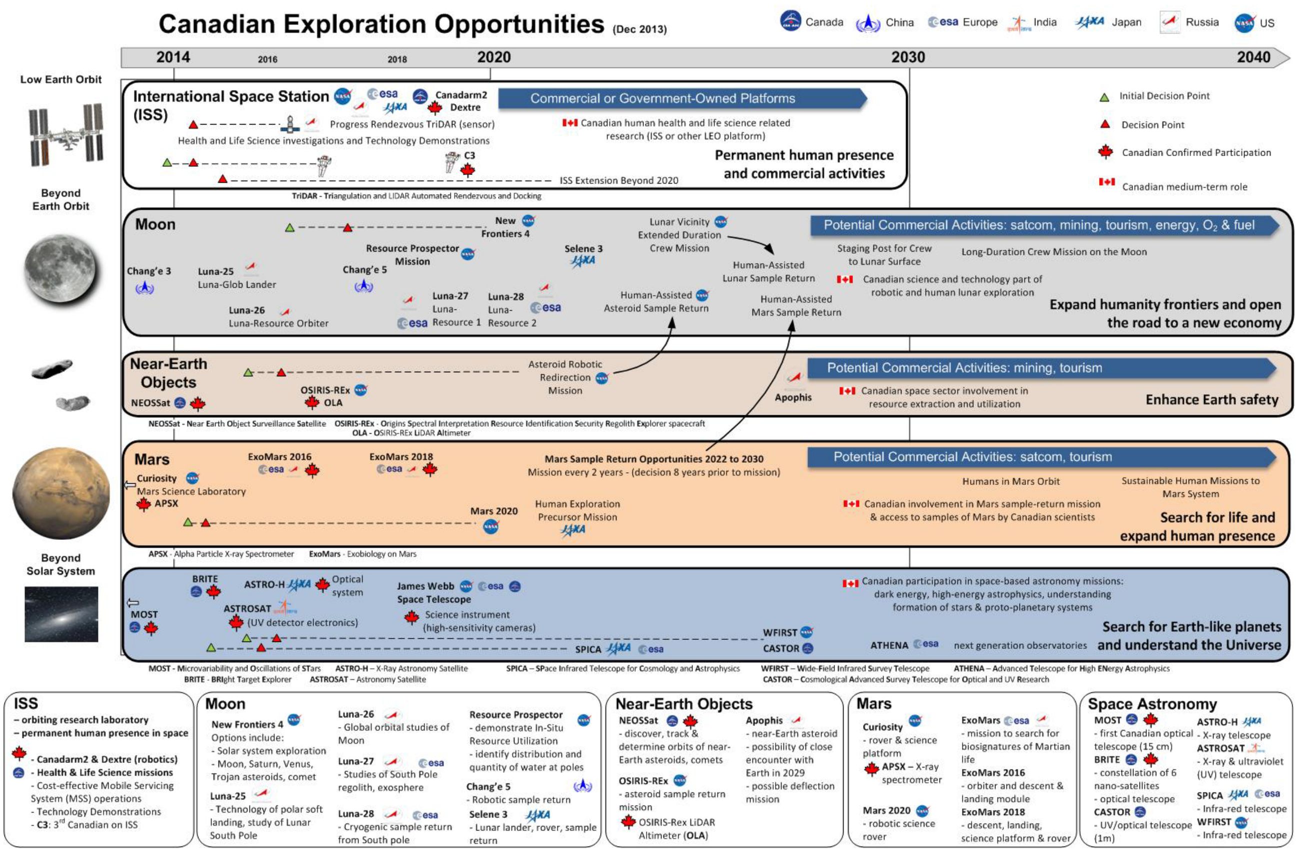

Figure 1 - Roadmap of Space Exploration Missions

CSA in order to maintain Canada's industrial positioning. CSA is conducting OOS technology demonstrations on the ISS and will continue to do so throughout the life of the ISS. These are captured in the roadmap under the Technology Demonstration line.

Technologies being targeted include evolution of robotic manipulators, specialized tools for on-orbit servicing and vision systems for inspection and orbital rendezvous.

2.2 Moon

The Lunar portion of the roadmap contains several international missions including China's Chang'e 3 mission, which has already successfully landed the Yutu rover on the Moon [1] as well as upcoming missions planned by several space agencies. The roadmap also includes potential manned missions in cis-lunar space such as a Deep-Space Habitat that could serve as a staging post for human exploration or for NASA's concept of an asteroid redirect mission [2].

No firm commitment has yet been made by Canada on any of these missions but discussions are on-going to identify a potential Canadian role on many of these.

Canadian capabilities that could be contributed to an eventual lunar landed mission include rovers, robot manipulators, vision systems (passive or active), drills and hazard detection sensors/systems for planetary landing. Potential contributions to missions in cis-lunar space are the same as those identified for the ISS and on-orbit servicing applications.

2.3 Near-Earth Objects

The roadmap for missions targeting Near-Earth Objects is very slim at the moment. Canada is already quite active in this field with a microsat observatory (NEOSSat) and the provision of a Laser altimeter on NASA's OSIRIS-Rex mission.

The only other opportunity for Canadian robotic technologies at the moment is NASA's asteroid redirect mission concept.

Long-term Canadian interest in NEO includes eventual extraction and utilization of in-situ resources.

2.4 Mars

Finally, the last element of the mission roadmap that is relevant for robotic technologies is the exploration of

Mars. Canada is also already active in Mars exploration through the provision of an Alpha-Particle X-ray Spectrometer on NASA's Curiosity rover, the high-gain communications antenna on ESA's ExoMars 2016 orbiter, part of the rover drivetrain (Bogie Electro-Mechanical Assembly and Actuator Drive Electronics) and navigation cameras on ESA's ExoMars 2018 rover.

For the Canadian science community, the ultimate goal of the Mars exploration program is to have access to Mars samples that will eventually be obtained through a Mars Sample Return (MSR) mission.

Participation in future Mars mission opportunities opening the door to MSR is therefore being envisaged. Potential Canadian contributions to future Mars landed missions are similar to the ones being envisaged for lunar missions: they include rovers and rover sub-systems, robot manipulators, vision systems (passive or active), as well as drills and sample capture mechanisms.

3 Development Activities

The methodology of the CSA's development programs starts with concept studies that result in mission and technology roadmaps. These roadmaps detail the development work required to ensure the availability of technologies in a timely fashion in order to reduce programmatic and technical risks during the project phases. Once the technologies are identified in roadmaps, they are developed under prototyping programs, and then deployed in field trials and analogue missions. These trials are used to validate the prototypes, increase operational readiness and refine the subsequent prototyping phases. The final outcome of the products of the development program is the use of the technologies in flight programs, or better yet, their commercialization in space and/or via terrestrial spin-offs.

3.1 International Space Station and On-Orbit Servicing

The Mobile Servicing System (MSS) has been operational for years on the ISS: The Canadarm-2, which was used to assemble the station as early as 2001, is now used routinely to capture visiting vehicles. Dextre, the space station handyman is used to conduct robotic maintenance operations such as replacement of Orbital Replacement Units. It is also used in support of technology demonstration experiments such as the Robotic Refuelling Mission payload, which has demonstrated in-orbit several delicate operations that would be expected in satellite servicing: removing fuel caps and transferring fuel into a satellite not originally designed for robotic maintenance [3].

To complement these capabilities, a launch adaptor ring capture tool prototype is currently under development. It is designed to capture rings of varying diameters from 937mm and larger. It has a quick soft capture reaction time and it uses a vision system to ensure that operations need not rely on high-bandwidth, low-latency communications with a ground-based operator. This tool could eventually be made compatible with Dextre's robotic interfaces and be tested as part of a Development Test Objective (DTO) on the ISS. It is also being envisaged for a deorbit mission to bring down the now-defunct EnviSat.

The capabilities developed in Canada through the Shuttle and ISS programs have positioned industry to participate to international OOS missions. In 2007, MDA had provided robotic elements for DARPA's Orbital Express mission. Today, MDA is involved in DARPA's Phoenix mission: a novel concept that is proposing to combine assets harvested from defunct satellites in geosynchronous or graveyard orbit with satlets to create new functional satellites using a modular philosophy. Individual satlet modules provide basic functionality such as attitude control, communications, computing or other services. When aggregated, satlets combine to provide the functionality of a full satellite. MDA is providing three elements to the Phoenix mission: the first element is the Payload Orbital Delivery System (PODS) that delivers satlets and payloads to GEO using surplus upmass on commercial satellites. The second element is the situational awareness cameras, and the third is a set of robotic servicing tools: namely a capture tool for the free-flyer capture of the PODS, a general-purpose gripping mechanism.

In addition to robotic elements, Canada has provided several camera and vision systems for the ISS and other vehicles in Low Earth Orbit. On the ISS, camera and light assemblies have reached the end of their useful life and are in need of replacement to meet the requirements of the 2020 ISS lifetime. Concept studies were conducted to investigate opportunities that could be opened by the replacement of ISS cameras. Among options considered were higher resolution cameras (e.g. HD Cameras) or the incorporation of additional sensing modalities such as a laser-based active vision system. In line with this study, a prototyping activity is currently under way to develop a TRL-6 prototype of a Rendezvous Navigation Lidar Sensor that could be installed on the ISS to track incoming visiting vehicles. The current prototype is derived from Neptec's TriDAR sensor that was used on US Space Shuttle flights [4]. The requirement is to track vehicles in the range of 20m to 1km. From 20m to 200m, the system will provide 6 degree-of-freedom pose; beyond 200m, the system will provide azimuth, elevation and range.

The expertise developed through prototyping activities and camera upgrades would be directly applicable to the design and fabrication of a flight system currently being considered for launch on the ISS: The Dextre Deployable Vision System. The DDVS payload is currently being proposed to NASA as a permanent facility that would include high resolution cameras, a LIDAR-based sensor to track incoming vehicles docking to ISS' node 2, and a higher resolution sensor structural inspection to detect micrometeoroid impacts. In a similar vein, Roscosmos is currently investigating mounting a TriDAR sensor on its Progress vehicles as a replacement/complement for current navigation sensors.

An additional unforeseen success of the CSA's Exploration prototyping program is the recent usage of an avionics card that was developed as a generic payload interface in the Exploration Surface Mobility project performed under the economic stimulus program: the Q6 electronics card developed by Xiphos technologies. Since delivering the prototypes to the CSA, Xiphos has flown Q6 cards on 2 microsatellite missions led by SpaceQuest in 2011 and on stratospheric balloon flights in 2013. In addition, the card is now used as a protocol converter on the e-OSTEO payload that was initially flown on a Russian Foton capsule and is now being prepared for an ISS flight [5]. This opens the door to eventual re-use of the Q6 to interface science payloads on the ISS. In fact, five studies are currently under way to detail life sciences and medical payloads for future flights on the ISS: the Q6 is the baseline solution for three of these studies and is being studied by the other two.

Finally, the technologies developed in support of ISS and on-orbit servicing have also resulted in terrestrial spin-offs in the medical domain. MDA has developed the NeuroArm: a robotic manipulator for brain surgery that is compatible with Magnetic Resonance Imagery equipment (see Figure 2). As of November 2013, NeuroArm has already been successfully used in clinical trials on 50 patients. The robot improves precision and accuracy over traditional surgery conducted by a specialized neuro-surgeon [6].

Similarly, MDA is working with the Hospital for Sick Children in Toronto to develop a surgical manipulator to reconnect delicate vessels such as veins, arteries or intestines on children or babies. The KidsArm uses virtual decomposition control software [7] that was transferred from CSA to MDA under the Next Generation Canadarm project [8].

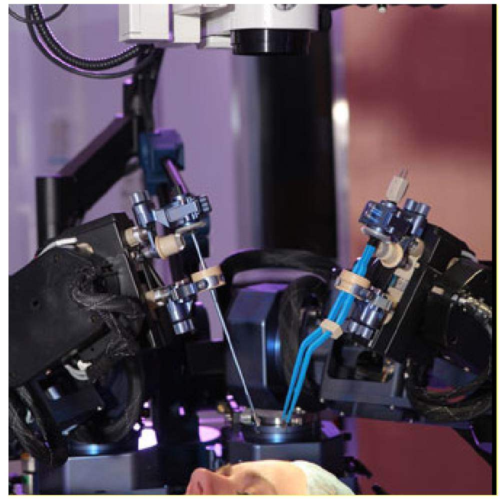

Figure 2 - NeuroArm. Image courtesy of University of Calgary

3.2 Moon

A natural extension of Canada's expertise in orbital robotics is the use of these technologies for planetary missions. As indicated on Figure 1, Canada does not yet have a confirmed participation in a lunar mission. However, several development activities have been undertaken to extend the existing capabilities. Most of these activities in the past two years have been targeted at enabling participation to NASA's Resource Prospector Mission (RPM) [9] or similar lunar landed missions.

Three concept studies have been conducted specifically to support the definition phase of RPM, leading to the mission concept review. The studies were used to develop the concept of operation and to identify the main technical risks to be addressed before committing to the mission.

One of the issues identified in the concept studies was the necessity to validate and characterize the expected performance under the selected operations concept. To minimize costs and complexity, the studies recommended that the rover and associated equipment be controlled via teleoperation. However, delays on the order of up to 10 seconds, associated with bandwidth limitations are expected given the landing site location and the communications infrastructure.

Field trials were therefore conducted using the CSA's Juno rover platforms [10] (See Figure 2) and the CSA's Symphony software suite to implement the ground stations. Different operator interface modalities and tools were implemented and characterized in terms of driving distance efficiency, error rates and operator fatigue.

Operator inputs were allowed in velocity mode through hand-controllers, as well as in position and trajectory modes through mouse clicks in camera views. The appropriateness of camera views to provide sufficient situational awareness was also evaluated by forcing the operators to drive through challenging environments. Two field campaigns were conducted using teams of operators that had not seen the terrain ahead of time. Operators were picked from different background and were not the experts that had developed the rover ground station tools, or the rover software. The results of these test campaigns are presented in [11].

Figure 3 - Teleoperation Rover Testbed Configuration for Field Campaigns

The studies also identified technical risks that needed to be addressed before committing to the mission. As a result, a study is currently being conducted to evaluate the effect of lunar regolith on robotic components. Wear tests are being conducted using lunar simulant under thermo-vacuum conditions. Dust mitigation strategies will then be devised based on the outcome of these tests and the experiments will be repeated after implementation of the mitigating solutions. CSA will also soon undertake activities to design and build a TRL-6 lunar rover drivetrain and a study on thermal design solutions for lunar night survival.

Also as an outcome of the concept studies in support of the RPM mission, a prototyping contract is underway to prove the feasibility of a direct-to-Earth communication system for a lunar polar mission. The selection of teleoperation as the control mode implies the ability to continuously point a high-gain antenna at a very low inclination angle with respect to the horizon. The short duration of the RPM mission also implies that driving speeds are sufficiently high to conduct the entire mission in less than one lunar day since the current concept does not assume surviving the lunar night. This activity will result in the fabrication of a prototype that will be field-deployable on any vehicle to test the technology under different driving conditions.

In support of future mission opportunities, the CSA is also investigating the development of active vision technologies for rover navigation. Active sensors such as LIDAR have the ability to provide three-dimensional, long-range terrain data with little sensor noise, even in total darkness. A contract is currently under way to increase the technology readiness level of a panoramic LIDAR sensor for rover navigation. It is based on the existing prototype of an integrated vision and imaging geological mapping sensor (IVIGMS). The LIDAR-based mapping of IVIGMS will be upgraded to resist environmental conditions typical of lunar surface operations. It will be tested for vibration, thermal, vacuum and regolith resistance. The intent is to approach TRL-6, targeting a mass of 12 kg and power of 150W including thermal regulation.

Despite the advantages listed above, LIDAR sensors are still facing hurdles to their adoption as navigation sensors in rover missions. The main drawbacks of the current designs are their high mass and power consumption. To address these issues the CSA will soon start low-TRL prototyping activities to investigate technologies to reduce mass, volume and power.

Interestingly, the IVIGMS panoramic LIDAR sensor is already being commercialized by Neptec technologies for terrestrial applications [12]. Target applications include mounting on vehicles for applications such as mining.

Figure 4 - Ontario Drive and Gear's J5 Mobility Platform. Image courtesy of ODG

Another spin-off of the planetary rover prototyping activities is the commercial J5 platform recently released by Ontario Drive and Gear. The J5 is derived from the Juno/Artemis family of rover designs that were developed under the Exploration Surface Mobility project. The J5 platform is targeting terrestrial unmanned vehicle applications such as military, security or agriculture [13] (See Figure 4).

3.3 Near-Earth Objects

As evidenced by the mission roadmap presented in Figure 1, there is little on-going development activity towards missions to Near-Earth Objects. The only target mission on the horizon at the moment is NASA's Asteroid Redirect Mission, which has yet to be confirmed. The activities conducted by the CSA towards that mission are limited to studying existing Canadian capabilities that could be used for such a mission and establishing a baseline cost and schedule for the various options.

Two topics are of particular interest: robotic manipulators in support of the ARM mission and its infrastructure, and vision sensors for the asteroid rendezvous.

In terms of robotic manipulator capabilities, the proposed solution should be compatible with spacecraft solutions such as the Orion capsule or an eventual Deep Space Gateway spacecraft parked at the Earth-Moon Lagrange Point #2 (EML-2). Operations to be conducted by such a manipulator would be very similar to those being performed routinely on the ISS: capturing free-floating vehicles, supporting Extra-Vehicular Activities, and assembling or maintaining modules and infrastructure.

Sensor solutions would be expected to support asteroid rendezvous, proximity operations, characterization, and capture. The sensing systems should be capable of characterizing the asteroid's size, shape, mass and inertia properties, spin state, surface properties, and composition. Some of these capabilities already exist through solutions such as Canada's contribution to the Osiris-REX asteroid mission [14].

3.4 Mars

The last target destination for which development activities are conducted is Mars. The ultimate objective of CSA's Mars exploration program being access to returned samples, prototyping and deployment activities are geared towards identifying and developing technology solutions that would constitute acceptable contributions from Canada to ensure access to Martian samples for the Canadian science community.

The CSA has now undertaken a deployment campaign simulating the surface component of a Mars sample mission. The analogue test plan is compatible with the latest scenarios developed by the International mars Architecture for the Return of Samples (iMARS).

Operations include autonomous navigation of the rover to selected sampling sites, characterization and triage of the samples to be collected with rover-based instrumentations, collection of core samples and transfer to a sample encapsulation system, and autonomous return to the lander.

As a baseline, the test campaign will use prototypes developed under the Exploration Surface Mobility project: namely the Mars Exploration Science Rover (MESR), the Small Manipulator Arm, a mini-corer and associated sample encapsulation system, as well as a Three-dimensional Multispectral Microscope Imager.

Other science instruments will be added as required and as they become available. For example, a Laser Induced Breakdown Spectroscopy instrument is also under development and could be integrated at a later date. The test campaign will also build on previously developed capabilities in terms of autonomous software [15] and the Symphony ground station.

The objectives of the test campaign are to test and validate the existing prototypes and identify requirements for additional technology development. The campaign will also test sample selection protocols and validate the usefulness of various science instruments to support decision-making for sample selection.

Results are not yet available as the initial deployments are planned for summer 2014.

In terms of flight programs, Canada is participating to NASA's Mars Science Laboratory by providing the Alpha Particle X-ray Spectrometer mounted on the Curiosity rover. This instrument provides measurements of the abundance of chemicals in Martian rocks and regolith. It is now approaching the end of its two-year nominal operational life. An extension to the operations phase of the APXS instrument is being sought to support the extension of the mission of the Curiosity rover.

Canadian industry is also involved in the ExoMars landed mission through Canada's contribution to the ESA program. MDA is building the Bogie Electro-Mechanical Assembly: the drive-train of the ExoMars rover and a portion of its drive electronics [16]. Neptec is developing and delivering the ExoMars rover Vehicle navigation and Localisation Cameras [17].

4 Conclusions

Space robotics is an established Canadian key industrial capability with an internationally recognized reputation. Over the last 30 years, Canada has invested well in excess of $1B. Today, the Canadian Space Agency is investing in technology development activities to maintain that capacity and to open doors to opportunities in new categories of space missions.

On-going activities cover the full spectrum from ISS robotics, on-orbit servicing to planetary exploration. Technologies being developed include planetary rovers, robotic manipulators, sampling drills and vision systems. Some of the space activities have even led to the successful commercialization of products for terrestrial markets.

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