Canadian Activities in Intelligent Robotic Systems: An Overview

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Abstract

Space Exploration has been the subject of renewed interest as is clearly demonstrated by the creation of the International Space Exploration Coordination Group by 12 space agencies. Canada is determined to provide key technologies and expertise that will be critical for space exploration. Much of this expertise lies on a strong background in space robotics and in scientific instrumentation in the Canadian industry base, science community and internally in the Canadian Space Agency.

Recent Canadian activities in space robotics include the successful robotic operations on the Space Shuttle and on the International Space Station but also technology demonstration missions in low-Earth orbit to demonstrate on-orbit servicing. Other activities are preparing the future space missions on the ISS with Dextre, in advanced on-orbit servicing or for planetary exploration. Planetary and more generally space exploration is seen by Canada as the next opportunities to pursue the expertise in robotics that started 30 years ago.

1. Introduction

Most future space exploration missions will require robotics technology. Currently, there is a need for on-orbit rendezvous and docking. In the near term, there will be a need for more automated surface rover vehicles and manipulators to collect and handle samples on the Moon and Mars. Later, robotics will be needed on the Moon to provide mobility and manipulation capabilities for astronauts and to build habitats.

In the longer term, robotic systems will be required to bring samples back from the Moon and from Mars. Manipulators will also be needed to assemble large spacecraft in Earth orbit to carry crews bound for Mars. One day, manipulators may also be used to construct permanent structures in orbit around Mars.

One of the most critical elements for space exploration, either in orbit or on the Moon or Mars, is the ability to see. This ability must be combined with a capability to extract useful information from a scene. This is required for on-orbit rendezvous, planetary landing, planetary navigation and visual inspection of planetary samples.

With its history of providing Canadarms and vision systems for the Space Shuttle and the International Space Station (ISS) – Canadarm2 is still the only robotic manipulators routinely used in human spaceflight operations – Canada is well positioned to remain a favoured provider of robotic for use in space and on planetary surfaces. Canadian industry also participated in operational missions on the shuttle and on the ISS and to some in-space technology demonstration.

For sustained human exploration, it is also critical to extract and make use of materials to produce oxygen and water for life support. With its strong expertise in automated mining and space robotics, Canada can play a significant role in providing technologies for in-situ resource extraction and utilization. For example, mining expertise is helpful in developing technologies to extract oxygen and volatile compounds from lunar soils. Existing drilling hardware and software could ultimately be adapted to extraterrestrial environments.

While Canada currently enjoys a leadership position in space robotics, other nations have begun to develop similar systems. To maintain its edge, Canada is continuing to invest in R&D in this field, which will remain critical for space exploration endeavours.

2. Opportunities

2.1. ISS and Shuttle

The year 2008 will mark an important milestone for the Canadian participation to the International Space Station (ISS) program. Indeed, the launch of Dextre, planned for February 2008, will complete the delivery of the robotic elements of the Mobile Servicing System to the ISS.

Unlike assembly operations, which are carefully planned and choreographed, some of the maintenance operations to be conducted by Dextre will be triggered by equipment failures on the ISS. This will require a shift in the operations planning and verification procedures compared to the robotic operations that have been conducted on the ISS so far.

Another important aspect of the ISS from the perspective of space robotics is its potential usage as an experimental test-bed for technology experiments and human factor studies. In the short term, the ISS will be used to conduct remote operation experiments, whereby a cosmonaut, located on the ISS, will control Earth-based robots to evaluate concepts of operation for planetary exploration and to advance the technology readiness level of key technologies in autonomous robotics.

2.2. On-Orbit Servicing

The second area of opportunity is on-orbit servicing (OOS) of orbital assets. OOS has been used for many years already for high-value assets. Examples include the maintenance missions that were flown to upgrade the Hubble Space Telescope as well as all assembly flights for the ISS.

Recently, technology demonstration missions such as DARPA's Orbital Express and the US Air Force's XSS-11 have shown the technical viability of on-orbit servicing for satellites found in Low Earth Orbit (LEO).

Canada has developed world-leading expertise in orbital manipulators and in active vision systems for orbital rendezvous and robotic operations.

Upcoming opportunities include planned commercial missions such as SMART-OLEV, which is targeted at the geostationary orbit (GEO), the Commercial Orbital Transportation System (COTS) targeting commercial re-supply of the ISS as well as the Orion vehicle that is being developed as a replacement for the shuttle fleet.

2.3. Planetary Exploration

Finally, the third area of opportunity is planetary exploration. Canada was one of the fourteen agencies that participated to the drafting of the Global Exploration Strategy (GES): the framework in which nations have agreed to undertake a common effort towards the exploration of the solar system.

The GES has identified our moon as the first destination for any manned exploration mission and has acknowledged the significance of Mars as the prime target of scientific interest motivating much of the early development.

The GES proposes that the international exploration efforts be structured as a program of programs where nations will lead national or international missions that will complement each other and strive towards global advancement of exploration.

In this context, part of Canada's strategy would be to provide infrastructure contributions to international missions according to niche expertise. At the moment, relevant expertise exists in the following areas: surface mobility, robotic manipulators, vision systems, planetary landing systems and in-situ resource extraction.

3. Recent and Current Missions

3.1. Dextre

Dextre, formerly known as the Special Purpose Dexterous Manipulator (SPDM), has been designed primarily for servicing tasks on the exterior of the space station. It is composed of two 7-degree-of-freedom arms and a torso with a waist joint. Each arm is equipped with a specialised end-effector, a socket drive and camera/light units. The torso includes a Power Data Grapple Fixture (PDGF) at one end, which allows Dextre to be manipulated by the Canadarm-2. It also has a latching end-effector at the other end, allowing Dexter to be powered directly by a PDGF.

Dextre will be used to handle Orbital Replacement Units (ORU) located on the outside of the ISS. Typical ORU to be handled by Dextre vary from the size of shoebox to the 100 kg (220 lb) battery boxes used on the ISS. Dextre will therefore allow the conduct of several maintenance tasks that would otherwise demand a spacewalk from the ISS astronauts and cosmonauts. Dextre will nominally be controlled by an operator located at the Robotics Work Station inside the ISS. However, like Canadarm-2, plans are being considered to allow ground control thus saving precious crew time by delegating some tasks to ground support personnel.

Figure 1 - Dextre Components at Kennedy Space Center

Dextre was delivered to the Kennedy Space Center in June 2007 and is currently awaiting launch on STS-123 in February 2008.

3.2. Orbital Express

Another key accomplishment in space robotics in 2007 was the launch and operation of DARPA's Orbital Express (OE) mission [1]. The purpose of this mission was to demonstrate several satellite servicing operations and technologies including rendezvous, proximity operations and station keeping, capture, docking, refuelling, and ORU Transfer. The prime contractor for the mission was Boeing. MacDonald Dettwiler and Associates (MDA) provided all robotic elements including the manipulator, end-effector, vision systems and ground control console.

During its mission from March 2007 to July 2007, OE successfully demonstrated all of its planned objectives. One of the first scenarios was the automatic visual checkout of the two spacecraft using the manipulator-mounted camera. This operation was conducted soon after commissioning.

Later, fuel transfer and ORU transfer were demonstrated under the supervision of ground-based operators at varying levels of human intervention.

Eventually, near the end of June 2008, a complete autonomous rendezvous and capture manoeuvre was performed from a distance of 9km. After the successful capture, the robotic manipulator on board the ASTRO spacecraft (the servicer) performed an extraction and insertion of a spare flight computer on the target satellite NextSat.

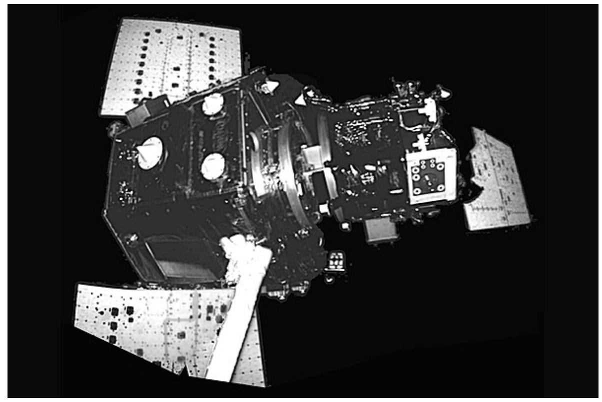

Figure 2 - ASTRO spacecraft capturing NextSat during Orbital Express mission[2]

3.3. XSS-11

Also in the area of On-Orbit Servicing, the US Air Force Research Lab launched the Experimental Satellite System-11 (XSS-11) in April 2005 on a one-year mission designed to demonstrate space technologies associated with autonomous rendezvous and proximity operations [2].

MDA and Optech provided the Rendezvous Lidar System (RLS) system that was used as the primary sensor on XSS-11 for rendezvous operations during its 22 months extended mission.

The 10kg / 75Watt RLS was designed to detect small space resident objects at ranges between 3km and 2m, track and image these objects under all lighting conditions.

Over the course of the mission extending into 2007, the XSS-11 mission has completed more than 75 natural motion circumnavigations of the expended launcher rocket body. The spacecraft has conducted rendezvous and proximity maneuvers with several U.S.-owned dead or inactive resident space objects near its orbit using incremental autonomy demonstrations of rendezvous and proximity operations, including multiple rendezvous maneuvers with the upper stage of the Minotaur I launch vehicle at distances between 1.5 kilometers and 500 meters.

3.4. Phoenix Meteorological Station

The Phoenix Mars Mission [3] is the first in NASA's Scout Program. Phoenix is designed to study the history of water and the habitability potential in the Martian arctic's ice-rich soil. In support of these goals, Canada has provided the MET instrument for this mission. Much of the experience being gathered

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[2] **Photo courtesy of Boeing**

through the Phoenix MET program will be transferable to the design of robotic equipment for planetary surface operations, in particular for issues regarding environmental conditions, planetary protection and operation protocols.

The MET instrument is actually a suite of three instruments. Their capabilities include the measurement of Mars' atmospheric pressure, surface temperature and its gradient as well as the height profile of atmospheric dust and cloud layers that drift past the landing site.

The LIDAR (Light Detection and Ranging) on the Phoenix mission uses two wavelengths of light and three different receivers to provide information on the properties of dust and water vapour and their layering in the atmosphere. It is capable of probing the atmosphere up to ranges of 20km.

Launched in August 2007, the Phoenix Spacecraft is currently in cruise phase of the mission with a planned landing in May 2008. Science operations including that of the MET will occur over a 5-month period until September 2008.

The next step in planetary exploration is the development of the Alpha Particle X-ray Spectrometer (APXS) that Canada will contribute to the Mars Science Laboratory mission scheduled for launch in 2009.

4. Flight Experiments

4.1. TriDAR

The Neptec Laser Camera System (LCS) has now been successfully operated on several missions to inspect the Space Shuttle's Thermal Protection System (TPS) [4]. The LCS has provided high-resolution 3D data of TPS tile damage providing mission critical data to ground controllers.

Based on LCS technology, Neptec has developed the TriDAR sensor. The TriDAR sensor combines auto-synchronous triangulation and Time-of-Flight (ToF) active ranging technologies within a single optical path. This configuration takes advantage of the complementary nature of these 3D imaging techniques and provides accurate 3-dimensional data at both short and long range [5]. By merging the subsystem's optical paths and using the same control electronics, the TriDAR provides the capabilities of two 3D scanners into a compact package. Furthermore, the TriDAR design is largely based on Neptec's Laser Camera System (LCS). Most of the system is, therefore, already space qualified. With its extended capabilities at both short and long range, the TriDAR is a flexible sensor that can be used for multiple space applications: rendezvous & docking, planetary navigation and landing, site inspection, material classification and vehicle inspection.

Figure 3 - LCS image of shuttle tile damage[3]

For Autonomous Rendezvous and Docking (AR&D) applications, Neptec has developed the ^{3D}LASSO model based tracking software [6], [7]. This technology was developed under the Canadian Space Agency's Space Technologies Development Program (STDP). When used with a TriDAR sensor, the software provides 6 Degree of Freedom (DOF) relative pose information in real-time from 3D sensor data without requiring cooperative targets. Real-time performance has been achieved by implementing a smart scanning strategy referred to as More Information Less Data (MILD). Using this strategy, only the data necessary to perform the pose estimation is acquired by the sensor thus minimizing the acquisition time and processing required. Neptec's AR&D vision system technology readiness has been demonstrated at several customer facilities including the Flight Robotics Laboratory (FRL) at the NASA Marshall Space Flight Center. Both open loop trajectories (nominal and off-nominal) as well as closed loop real-time docking operations have been tested. Opportunities are now being sought to conduct a flight experiment on a shuttle flight.

4.2. Avatar

Avatar is a series of space missions used to validate and increase the level of maturity of the autonomous robotic and software technologies developed at the Canadian Space Agency. In the first planned mission, Avatar RESCUE, it is proposed to conduct a semi-

[3] **Photo Courtesy of Neptec**

autonomous satellite capture operation using a laboratory robot commanded by a cosmonaut on the International Space Station (ISS) [8].

This experiment was already conducted several times successfully using the CSA's Automation and Robotics Testbed (CART) controlled from remote locations using low bandwidth Internet links. CART is a dual-manipulator facility. One arm emulates the free-flyer dynamics and the second is the chaser robot equipped with a SARAH hand. The Laser Camera System (LCS) from Neptec is used to guide the target robot.

An amateur radio already available on the Russian segment of the ISS will be used to communicate with a ground radio counterpart located at the CSA facility in St-Hubert. The operations will be conducted during the 8-10 minute communication windows when the ISS flies over the CSA headquarters. This mission is planned for the spring of 2008.

During a second phase, it is planned to use the same concept to conduct a planetary exploration scenario where an astronaut on the ISS will control a rover in the CSA's Mars emulation terrain from the ISS.

In the scenario, the rover will first take a 3D scan of its environment and transmit it to the operator on the ISS. The operator will then select an interesting area for science investigation and send a high-level command to the rover to proceed and move to that location.

Since the communication window with the ISS will only be possible during direct line of sight, which will last at most 10 minutes, this operation will be conducted fully autonomously without any communication link with the operator. Once the communication is re-acquired during a subsequent orbital pass, a batch of telemetry and terrain scans of the environment will be sent to the operator to allow him to plan the next sequence of operations. This second Avatar mission is being planned for 2009.

4.3. SMP Experiments

The operations of space robots require significant crew training both on ground and on orbit. A number of psychological and physiological factors are known to affect the crew on-board performance. Skills degrade over time depending on the frequency of operations, depth of proficiency and the usage of refresher training.

Since 2003 the CSA has been conducting experiments using the Systems for Maintaining and Monitoring Mobile Servicing System Robotic Operator Performance (SMP in short) to study the evolution of fine motor skills and 3D mental image reconstruction for tasks involving the operation of all robotic components of the Mobile Servicing System (MSS) of the International Space Station (ISS) [9].

The long-term goal of this research project is to gather data to study the degradation and recovery of psychomotor and cognitive skills. This data will be analyzed to help define metrics that could be used to assess the level of readiness of an operator to perform complex tasks. To study performance degradation and skill recovery, a highly efficient simulator is required in order to ensure on orbit real time simulation and fast feedback to the operator. In this project, the challenge is the real-time simulation of Canadarm2 and Dextre while performing graphics rendering of the worksite environment using just a single laptop computer.

From 2003 to 2007, several Expeditions (7, 8, 9, 10, 11, 14, and 15) have carried out several hundreds of pre-flight, in-flight and post-flight SMP sessions. A preliminary data analysis has already been performed and a more detailed analysis is currently in process. Furthermore, the SMP simulator is currently being integrated into the German system Neurolab 2000M as one of several of stimuli types. In the Neurolab system, the operator performance assessment is combined with a psycho-physiological approach for the objective assessment of the levels of physiological arousal and psychological load.

5. Technology Development Activities

5.1. Planetary Drilling

NASA and CSA funded projects have allowed the evolution of new techniques and technologies in support of missions to the moon, both robotic and human. These advancements take the form of significant improvements in autonomous operation and investigations into cryo-capable mechanism development and testing. The driver is essentially the desire to establish an outpost near the lunar south pole at the rim of a permanently shadowed crater. Surface temperatures in the permanent shadow are expected to be in the 40-Kelvin range. Sunlight shadowing would also mean radio shadowing and a preclusion of tele-operations.

RESOLVE is a NASA funded project for the investigation and characterization of subsurface volatiles and water content in permanently shadowed areas. The lead module is the drill developed by the Northern Centre for Advanced Technology (NORCAT), which is intended to acquire samples from regions up to 1 metre below surface for use in the analytical sections of the package. The drill and sample acquisition system must be autonomous, as the ability to tele-operate from earth, even with an orbital relay asset, is not practical. The drill team has evolved a highly autonomous control strategy that will allow the drill to complete its task of acquiring samples from subsurface while maintaining an ability to determine and manage off nominal events related to geophysical characteristics.

To enable drilling autonomy, NORCAT, in conjunction with Neptec and Xiphos Technologies, are developing a vision system for drill site triage. This system is intended to determine if a potential drill hole is likely a viable hole based upon surface geo physical characteristics. The system relies upon the Neptec Tri-DAR system for use in permanent shadow conditions such as might be found at a permanently shadowed crater drill site. The system has the ability to determine geophysical characteristics at standoff distances approaching 40 metres from a mobility platform. This information will guide the mobility platform destination navigation and guidance decisions. Once the drill platform arrives at the potential drill site, the vision system is targeted at the immediate area of the drill hole to determine the best spot to start the drill hole.

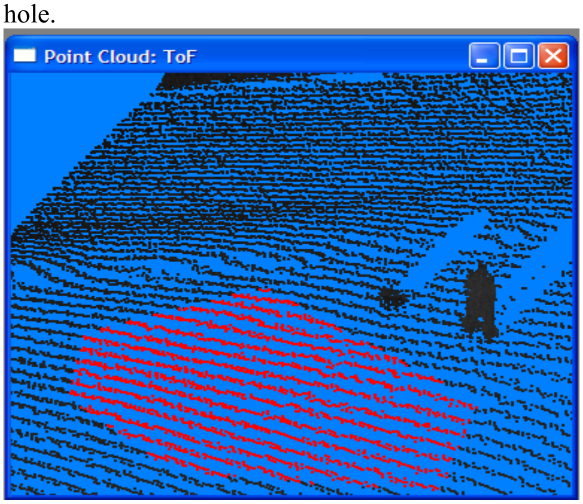

Figure 4 - Neptec TriDAR point cloud with geo physical overlay[4]

The system has recently been tele-operated remotely over a Ka band satellite link from CSA Payload Tele-Operation Centre (PTOC). The link allows the RESOLVE system to be installed anywhere in North America without any significant changes required at PTOC. The system is scheduled to undergo a second test in December 2007 where it will be mounted on a Scarab rover from Carnegie-Mellon University.

Finally, in order to prove operations in cryo-level temperatures, NORCAT has designed and tested "down the hole" hardware for the RESOLVE drill. This hardware was designed to provide functionality in sample acquisition at 40 Kelvin. A drill bit, auger, active sample capture mechanism, anti abrasion coatings, lubricants, and gas seals have been designed and successfully tested. Testing was performed in a custom designed cryo chamber at 1 atmosphere at temperatures of 90 Kelvin. (See Figure 5) The chamber allows a sample of OB-1 (NORCAT's lunar physical simulant with varying water contents to be cooled to 90K and held at that temperature while the down the hole components are exercised.

Figure 5 - Core capture mechanism after test at 90 Kelvin[5]

5.2. Planetary Landing Systems

Future exploration missions to the lunar or Martian surfaces will require the ability to land in a particular region of interest, either for targeted scientific study, identification of *in situ* resources, or establishment of a manned presence. In the past, the only suitable landing areas have been those with relatively flat, hazard-free terrain over the entire uncertainty ellipse of the landing spacecraft. However, the desired landing areas for future exploration and utilization missions will almost certainly have terrain that does not meet these criteria. Consequently, there is a clear need for an intelligent landing sensor system that can detect hazards and

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[4] **Image courtesy of Neptec**

[5] **Photo courtesy of NORCAT**

guide the lander to a safe landing site identified during descent.

The Canadian Space Agency has recently funded several advancements to the Lidar-based Autonomous Planetary landing System (LAPS), through the partnership of the Canadian companies MDA, NGC Aerospace, and Optech [10]. Lidar-based systems enjoy many advantages over competing hazard detection technologies. Unlike camera-based systems, the lidar is an active illuminator, which allows landing during the night, in shadowed polar regions, or within the interior of a crater. Scanning lidar has better spatial resolution, less mass, and lower complexity than radar-based systems. A credible design reference mission has been established for a LAPS-enabled hazard avoidance landing on the Moon or Mars, and has been shown to be favourable when compared to the Human-in-the-Loop hazard avoidance landings performed during the Apollo missions.

The Advanced Lidar-Based Navigation (ALBAN) technology was developed under a study funded by the Canadian Space Agency and led by NGC Aerospace. This innovative Canadian technology increases the current functionalities of the Canadian landing Lidar technology by adding absolute navigation to the existing LAPS technology.

ALBAN is a Terrain-Relative Navigation (TRN) landing technology that tracks features in consecutive Lidar images taken of the surface of the celestial body during the descent phase. Absolute navigation is obtained by matching detected surface landmarks from Lidar images measured in real time during the descent with a 3D model of the landing area constructed from orbital imagery. With this technology, both velocity and the absolute position of the Lander can be determined with accuracy during the descent phase and in any lighting conditions, contrary to solutions using optical sensors.

The ultimate objective of the ALBAN technology is to provide future Moon and Mars landing vehicles with the level of navigation accuracy required to land within a distance of 100 m from a desired target on a planetary body. This level of accuracy is precisely what will be required in future ESA and NASA Mars and Moon planetary exploration missions.

In order to test the planetary landing technologies, a Landing Dynamic Test Facility (LDTF) has been developed by NGC. This unique facility provides a cost-effective solution for the real-time testing and validation of landing guidance, navigation and control (GNC) algorithms in a dynamic environment [11]. The system reproduces in a scaled environment (1:50) the 6-DOF motion dynamics of a Lidar-based landing system relative to an emulated scaled model of the surface of Mars (Figure 6) in order to validate hazard detection and avoidance soft landing algorithms and terrain relative absolute navigation algorithms.

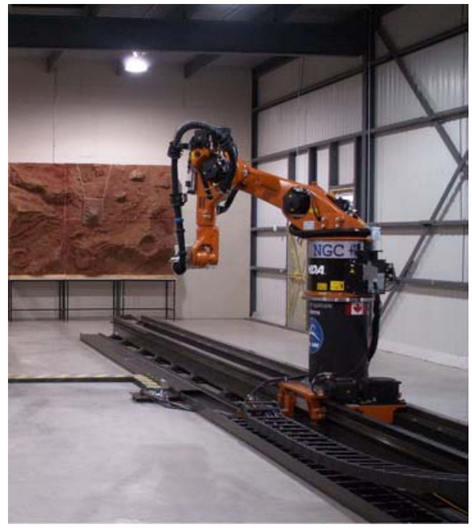

Figure 6 - Landing Dynamic Test Facility[6]

One of the main features of the LDTF is a robotic arm on a 15-meter long rail system (7-DOF robotic system). The controller is designed to reproduce spatially and time scaled landing simulations that are representative of Mars and Moon missions. It is also designed to interface with flight microprocessors containing the coded GNC algorithms to be tested. The LDTF uses an ILRIS-3D Lidar from Optech Inc. as the landing sensor.

Technologies currently being tested in this facility include Lidar-based hazard detection and avoidance, Lidar platform stabilisation and motion correction and Lidar-based terrain relative navigation.

5.3. Planetary Rover Test-beds

A few planetary rover test-beds are currently operational in Canada. MDA's Rover Chassis Prototype (RCP) has been developed to evaluate planetary rover chassis mobility. This test bed has the instrumentation necessary to perform system-level experiments in rover mobility and to use the hardware for validation of the Rover Chassis Analysis and Simulation Tool (RCAST).

The Rover Chassis Prototype is a six-wheeled, 21 degree-of-freedom (18 active DOFs + 3 passive DOFs) prototype providing accurate full-scale kinematic and dynamic representation of the EMRCB-E (Concept E)

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[6] **Photo courtesy of NGC Aerospace**

flight rover chassis selected for the ExoMars Phase A studies.

The chassis comprises three pairs of wheels (front with middle, and rear) installed on longitudinal-level rocking suspension. In addition to the six wheel drives, the RCP has six steering joints/drives and six walking joints/drives, each equipped with an encoder. Inclinometers measure the angular displacements of the three modules of the chassis, and an on-board video camera monitors wheel sinkage. In addition, the RCP is equipped with six force/moment sensors below each steering axis. RCP mobility testing and data collection was carried out in the MarsDome at the University of Toronto Institute for Aerospace Studies (UTIAS) and at the CSA's MarsYard. Test scenarios included step-obstacle negotiation and slope climbing for a variety of terrain cases.

Figure 7 - MDA's rover chassis prototype[7]

Following on from its ExoMars Phase A rover conceptual design, MDA has entered a phase B1 project for the analysis, design and hardware development aimed at addressing the critical issues for the Chassis and Locomotion (CLS) system for the ESA ExoMars program. One of the objectives of the project is to develop CLS flight design through a trade-off of suspension and locomotion concepts based on stability, mobility and terrain ability considerations. This includes flight avionic architectures and their associated mass, volume and power considerations. Another objective is to produce and test a CLS breadboard model, which will provide a representative platform to explore locomotion performance issues and to facilitate the development of locomotion techniques, algorithms and implementations

Both functional and performance testing of the breadboard system will be performed in a representative environment at the UTIAS MarsDome. Testing will also be used to validate the suspension and locomotion concepts proposed for the CLS flight design. Following this project, the end user (Astrium/ESA) will use the breadboard as a test platform for further mobility testing and GN&C testing which includes visual localization techniques.

5.4. Rover Navigation

In addition to the development of rover platforms, much technology development was performed in autonomous navigation both at the Canadian Space Agency (CSA) and at MacDonald Dettwiler and Associates (MDA). For autonomous navigation in natural 3D terrain, localization and terrain modeling become the key aspects of onboard rover functionality. CSA's work has concentrated on autonomous over-the-horizon navigation whereas MDA's work has concentrated on local navigation with emphasis on visual motion estimation and Simultaneous Localisation and Mapping (SLAM) combining stereo cameras, wheel odometry and inertial sensors.

Over the past two years, CSA has implemented and extensively field-tested navigation technologies concentrating on efficient and compact terrain modelling from LIDAR and path planning (in particular, the intricacies of marrying long-range and short range path planning) [12].

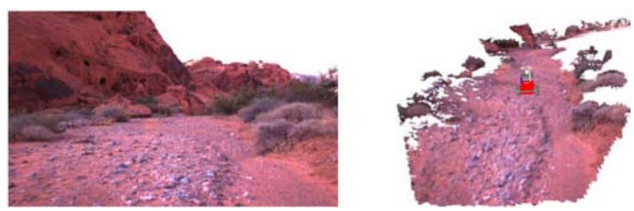

Figure 8 - Terrain model reconstruction based on MDA's vision algorithms[8]

An integrated autonomous navigation system has been developed and tested in realistic terrain in late 2005 in the Mojave Desert, USA (Figure 8). An upcoming test campaign in winter 2008 will rigorously characterize the performance of visual motion estimation and integrate the CSA's long-range navigation capabilities with MDA's short-range algorithms. So far, CSA's algorithms have been successfully tested in the field and have allowed over-the-horizon traverses of 100 to 150 meters in fully

[7] **Photo courtesy of MDA**

[8] **Image courtesy of MDA**

autonomous mode and MDA's visual odometry implementation has allowed for accurate real-time localization (i.e. less then 2-4% of distance traveled) at rover speeds up to 25 cm/s and 10 deg/s over traverse distances of 120m in outdoor realistic environments.

6. Conclusions

Space Robotics is a key element of the Canadian Space Program. The Government of Canada, through the Canadian Space Agency, has made a sizeable investment in space robotics, and several exciting programs are currently ongoing. Canada is providing sophisticated hardware as the main robotic system to be used for the construction and operation of the International Space Station.

In the recent past, the Canadian space industry has been able to capture mission opportunities in space robotics purely based on commercial merit.

Strategic robotic technologies are being developed in industry, academia and the CSA's laboratories with a strong emphasis on active vision systems for orbital rendezvous and planetary landing, in-situ resource utilisation and planetary rovers. These fields complement the traditional Canadian niches in space manipulators and artificial vision.

As Canada is increasing its participation in the global exploration initiatives, these developments are crucial to plan for the next generations of space robotic systems to be contributed to international missions.

7. Acknowledgments

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