ROBOTIC TECHNOLOGIES FOR SPACE EXPLORATION AT MDA

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ABSTRACT

For many years, space robotics has been a key element of the Canadian Space Program with over $2B of total investment. Robotic arms designed and built by MDA are used on virtually all flights of the Space Shuttle and are operating on the International Space Station. MDA is also providing sophisticated robotic systems for autonomous satellite rendezvous and servicing missions including the robotic repair of the Hubble Space Telescope. Building upon this strong heritage, MDA is setting its sights beyond Earth orbit toward the exploration of the moon, Mars, and beyond. Strategic technologies are being developed to allow Canada to continue as a leader in space robotics, and provide the critical robotic systems for this next chapter in humanity's exploration of space. This paper provides an overview of the work ongoing at MDA to continue to advance space robotic capabilities ranging from rovers to flight experiments to complete mission designs.

1. INTRODUCTION

For over two decades, space robotics has been a key element of the Canadian Space Program with over $2B of total investment. MDA has accumulated over 25 years experience in designing and building space robotics hardware, in which time it has achieved world renown for the Shuttle Remote Manipulator System (SRMS), first delivered in 1981 and continuing ever since as a workhorse for both the Space Shuttle and assembly of the International Space Station, and its successor the Space Station Remote Manipulator System (SSRMS), two-thirds of which are presently in operation with the final element awaiting launch. The flawless performance of the SRMS and SSRMS systems to date has undoubtedly been contributory in earning Canada its reputation as world leader in space robotics, however in recent years MDA has been successful in further developing robotic technologies for application beyond the Shuttle and Station programs (see Fig. 1), and is now continuing this story of success in the rapidly advancing area of autonomous satellite rendezvous, satellite servicing, and to exploration of the Moon, Mars and other planetary bodies beyond.

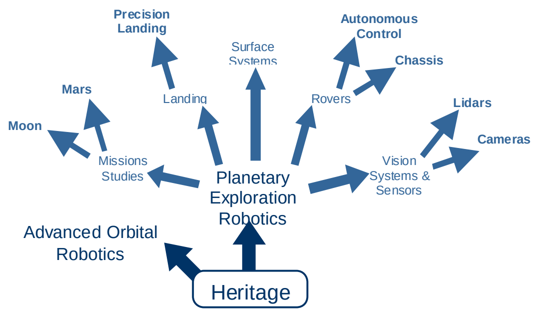

Fig. 1. MDA path towards robotic space exploration

These strategic technologies will not only allow Canada to continue its leading role in the field of space robotics, but furthermore will provide the critical robotic systems for this next chapter in humanity's exploration of space. This paper provides a summary of the work ongoing at MDA, commencing with a discussion of the space robotics heritage – past and present - in Earth orbit, before then proceeding to an overview of MDA's activities in robotic space exploration, from spacecraft systems through flight experiments to complete mission designs.

2. HERITAGE

2.1. Shuttle Remote Manipulator System (SRMS)

Fig. 2. Shuttle Remote Manipulator System

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As the Prime Contractor for the Shuttle Remote Manipulator System (SRMS), MDA developed the first of its kind “soft capture, hard dock” solution in the late 70s for handling payloads and capturing free flyers on NASA’s Shuttle Fleet (see Fig. 2). The innovative design, along with its associated robotic interfaces, became the robotic interface standard on the Shuttle and the International Space Station Programs. MDA continues to improve on the fundamental technologies, creating new flight products and interface standards for free-flyer capture, payload docking, power and data transfer. Over the past 25 years the SRMS has performed flawlessly and over a dozen free-flying satellites have been successfully captured and retrieved by the SRMS, as well as notable satellite rescue and repair missions such as Solar-Max, Westar and Palapa B. The SRMS has also provided key support to the past HST Servicing Missions including its capture and berthing as well as positioning EVA astronauts.

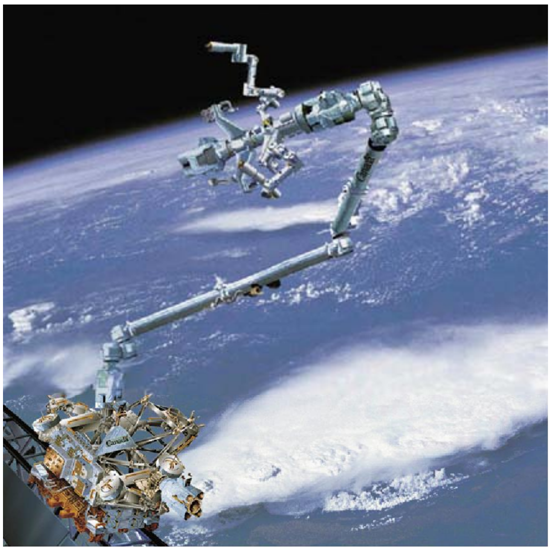

Fig. 3. Space Station Remote Manipulator System

2.2. Space Station Mobile Servicing System (MSS) (includes SSRMS, MBS, SPDM)

The Mobile Servicing System (MSS) provides the Space Station with advanced space-based robotics that is used to assemble, transport and maintain payloads in orbit, as well as to assemble the station itself. The MSS comprises three main elements: the Space Station Remote Manipulator System (SSRMS), the Mobile Base System (MBS), a smaller robot called the Special Purpose Dexterous Manipulator (SPDM), as well as important robotic interfacing subassemblies such as the Power & Data Grapple Fixture (PDGF).

The Space Station Remote Manipulator System (SSRMS) (see Fig. 3) is a seven degree-of-freedom manipulator approximately 57 feet in length. It features an arm with a central elbow joint and symmetrical clusters of three identical joints at both ends. Each end is terminated with an identical latching end-effector, allowing the arm to function with either end acting as a shoulder and the other end acting as a wrist. By grappling with the wrist end-effector, then exchanging wrist operations for shoulder operations within the same end-effector (involving switching power and data connections from one end of the arm to the other), and then releasing the opposing end-effector, the SSRMS can effectively walk head-over-heels along a series of grappling points. Using this capability, the arm can self-relocate between several different operational locations on the Station. Normally it operates from the Mobile Base System (MBS) attached to a mobile transporter that traverses the length of the Space Station truss. The SSRMS is a critical Space Station asset that has been used to help assemble the on-orbit station, and subsequently to deploy or retrieve payloads, and to transport astronauts. The SSRMS is also designed to capture and berth ISS visiting vehicles such as the Shuttle and the H-II Transfer Vehicles. It is a fundamental player in the maintenance of the ISS over its entire operational life. The SSRMS was successfully launched and commissioned in 2001 and has been operating on the ISS since. The MSS represents over US$1B space robotics development effort at MDA that provides a bedrock of flight-ready capabilities for the HST robotics servicing mission.

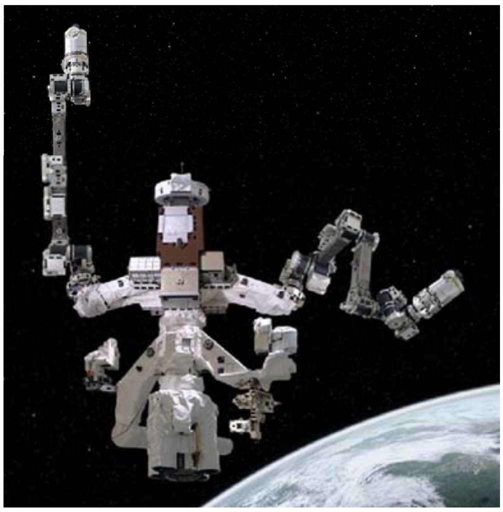

Fig. 4. Special Purpose Dexterous Manipulator

The Special Purpose Dexterous Manipulator (SPDM), see 9, is an advanced two-armed robotic system. It has sufficient dexterity to carry out the on-orbit maintenance of externally mounted Space Station hardware. It consists of a central body with a grapple fixture at one end and a latching end-effector at the other. This gives it the ability to operate either at the end of the Space Station Remote Manipulator System (SSRMS) or in a stand-alone mode, mounted on its own end-effector (see Fig. 4). Each of its two arms is identical, has seven joints, and is equipped with a tool change-out mechanism at the end. The mechanism can remotely change-out orbit-replaceable units and can also pick up and use special tools stored on the body of the SPDM.

The SPDM also incorporates automatic collision avoidance and has an advanced vision system. The SPDM has completed ISS flight certification and will shortly be prepared for delivery to Kennedy Space Center.

2.3. Shuttle Return To Flight

Fig. 5. OBSS for Space Shuttle Return To Flight

Following the tragic loss of Columbia in 2003, one of the requirements identified for resumption of shuttle operations was a way for NASA to inspect the underside of the shuttle before re-entry. MDA was contracted to develop the Inspection Boom Assembly (IBA), an extension boom to the SRMS that would support inspection of the Shuttle's Thermal Protection System (TPS) in-orbit.

The IBA is based on pre-existing hardware from the SRMS program, sharing almost exactly the same design except for the arm joints which are instead replaced with aluminium transitions, effectively freezing the joints in place. The tip of the boom is designed to accommodate and interface with a suite of sensors to assess the Orbiter's TPS.

Weighing 465 lbs. (excluding sensors), and nearly 50 feet long, the IBA is roughly the same dimensions as the Shuttle Remote Manipulator Arm. This similarity allows the IBA to fit neatly on the starboard side of the shuttle, where a holding mechanism was originally designed to support a second arm. Once in orbit, the SRMS and SSRMS can pick up and manipulate the IBA using grapple fixtures.

2.4. Hubble Servicing

As one of the most important scientific facilities of NASA and indeed of the world, the Hubble Space Telescope (HST) has created enormous interest in astronomy and in space science, contributing in the process fundamental scientific discoveries related to the origins of the universe, the structure and evolution of the universe, and the exploration of the solar system. Following the Columbia loss, NASA was forced to cancel its original 2005 HST servicing and 2012 HST de-orbit shuttle missions. In 2004 MDA was contracted by NASA to investigate the viability of both a reliable unmanned HST de-orbiting mission, and a robotic servicing mission to extend HST scientific life.

MDA recently demonstrated the viability of supervised autonomous robotic repair of the Hubble Space Telescope through a series of successful ground tests. The Hubble Robotic Vehicle Dextrous Robot (HRV DR) design was essentially a build-to-print version of the SPDM but with certain functionalities removed. The design featured two identical SPDM arms connected to a body structure, each capable of performing the servicing tasks, this twin arm configuration permitting stabilization of the DR, the use of a camera for worksite viewing and also providing mission functional fault tolerance.

Based on this design and the successful ground demonstrations NASA declared in February 2005 “A space-flight qualified robot has successfully demonstrated that all life-extension tasks and science instrument change-outs can be robotically performed”. However for reasons beyond the viability of the technical solution, NASA has since chosen not to pursue the robotic servicing of HST at this time.

2.5. XSS-11

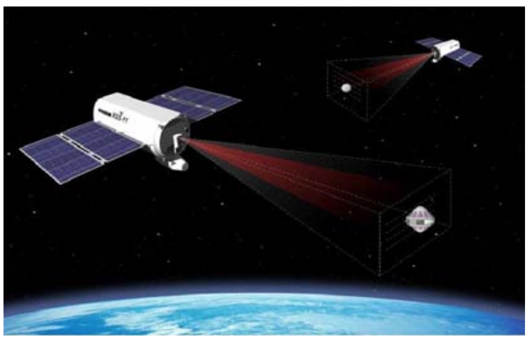

Fig. 6. DOD Rendezvous LIDAR demonstration

Along with its partner Optech Incorporated, MDA developed and delivered a Rendezvous LIDAR system (see Fig. 6) to the Air Force Research Lab (AFRL) XSS-11 flight demonstration launched earlier this year. The mission serves to demonstrate autonomous on-orbit operations and to advance those capabilities needed for a satellite to maintain operations on-orbit without intervention from ground-based mission control teams and assets.

The Optech/MDA Rendezvous LIDAR emits a burst of laser light and steers it using a two-dimensional, fast-scanning mirror. Measuring the time-of-flight and angle of the reflected beam provides the relative position and velocity of a target. This approach has some key benefits over typical methods of obtaining such data as it does not require pre-installed targets (such as retro-reflectors), does not require any external illumination sources and operates under extreme solar illumination conditions.

2.6. Orbital Express

The Orbital Express (OE) Program is an ambitious advanced technology program funded by the U.S. Defense Advanced Projects Agency (DARPA) designed to demonstrate the autonomous direct servicing of satellites on-orbit. The ultimate purpose is to develop the capability of servicing, repairing or refueling of commercial, civil or military satellites. An on-orbit demonstration of the feasibility of autonomous servicing technology is to be launched in 2006, with the intention of having the routine re-supply, repair, reconfiguration or upgrade of on-orbit spacecraft in place by 2010. A key factor in maximizing these new on-orbit capabilities is the development of a non-proprietary satellite servicing interface standard that can be implemented by any satellite manufacturer.

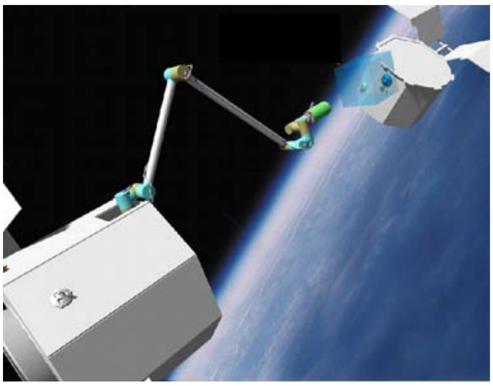

Fig. 7. DARPA Orbital Express Program

Currently being prepared for delivery, the robotics system that MDA is delivering can autonomously capture and service the target satellite, while also allowing ground control/intervention as need be.

3. EXPLORATION ROBOTICS

In 1998, MDA initiated a strategic business thrust in the area of space exploration robotics. Since then, the company has expanded its world leading position in earth-orbit space robotics to become a dominant provider of exploration robotic systems and missions targeted at the Moon, Mars, asteroids, and other solar system locations. MDA, in strategic teaming with several international partners, is developing planetary robotics systems and missions for NASA, ESA, and CSA as well as commercial space exploration opportunities. The following paragraphs describe some of these activities.

3.1. ExoMars

MDA acted as prime contractor to ESA for the design of the rover and science payload package for the 2009 ExoMars Mission Phase A study. During this program, MDA led an international team including Alcatel, Kayser-Threde, Alenia, and Carlo Galvazzi Space to develop concepts for a complete rover system shown in Fig. 8. The goal of the ExoMars mission is to characterize the Martian biological environment in preparation for future human and robotic missions.

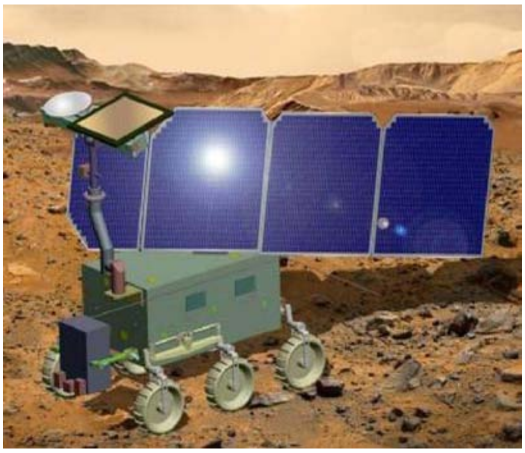

Fig. 8. MDA's ExoMars Rover

3.2. Phoenix Mars Lander

MDA is prime contractor to the Canadian Space Agency to develop the meteorological station (MET) for the 2007 Phoenix Mars Lander mission (see Fig. 9). The MET consists of a zenith pointed lidar, a set of mast mounted temperature sensors, and a pressure sensor. The science goals for the MET station are to investigate the Martian atmosphere and help characterize clouds, water transport, and dust content as well as validating temperature and pressure atmospheric models. The MET station will be the first Canadian science payload on the surface of Mars.

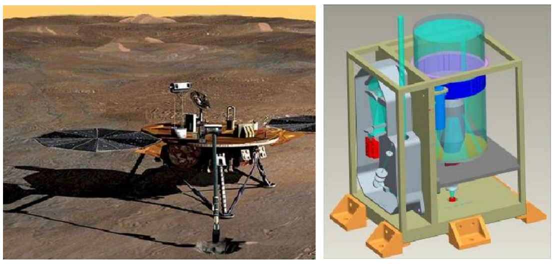

Fig. 9. NASA's Phoenix Mars Lander and MDA's Meteorological Station (MET)

3.3. Mars Science Laboratory

MDA was selected by NASA to provide the Alpha Particle X-ray Spectrometer (APXS) for the 2009 Mars Science Laboratory (MSL) mission (see Fig. 10). The APXS program will be funded by the Canadian Space Agency as Canada's contribution to the MSL mission. The APXS instrument has heritage from both the Mars Pathfinder and Mars Exploration Rover (MER) missions and is the only instrument to be carried over from MER to MSL. APXS is used to determine elemental abundance in soil and rocks and is critical in understanding the geological processes that have shaped Mars.

Fig. 10. NASA's Mars Science Laboratory (MSL) and MDA's Alpha Particle X-Ray Spectrometer (APXS)

3.4. Mars Instrument Studies

As part of its expanding suite of planetary science instruments, MDA is currently undertaking two studies for the CSA to conceptually develop additional instruments for geological and astrobiological investigation of the Martian surface.

A Borehole Gamma Ray Spectrometer (GRS) is being designed that will enable vertical and horizontal mapping of U, Th and K, through in-situ measurement in the local area being investigated by a lander or rover, and globally by providing ground truthing for the orbiting Mars Odyssey GRS. Borehole GRS measurements can also be used to distinguish between different rock types and detect alteration material within rocks and the instrument will be used not only for Martian igneous geochemistry investigation but, equipped with an active neutron source, will also directly validate the recent discovery of possible subsurface water ice detected by the orbiting Mars Odyssey spacecraft.

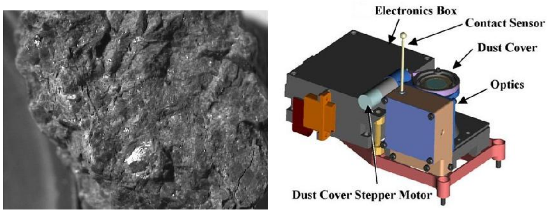

Fig. 11. Microscopic Imager

Secondly a Microscopic Imager is being designed that leverages MDA's heritage in spaceflight optical systems. The imager will be used in two modes: as both a contact science instrument, placed against surfaces that either have or will be examined by other sensors, or as a sample triage sensor studying in detail core samples and cuttings. Such images provide contextual information (see Fig. 11) for the interpretation of compositional data, can help characterise sedimentary rocks, and can yield information on small-scale rock features formed by volcanic and impact activity as well as tiny veins of materials like carbonates that may contain microfossils like those that were putatively identified in the Martian meteorite ALH84001. The shape and size of particles in the Martian regolith can also be determined by a microscopic imager, which may provide clues on how the regolith formed. It is commonly acknowledged that a microscopic imager will likely be flown on most future surface missions to Mars.

3.5. Planetary Surface & Subsurface Manipulators

Whilst MDA is recognised as the world leader in large scale space robotic manipulators such as SRMS and SSRMS, a host of new challenges are presented by the transition to the planetary lander and rover regime where mass, power and volume resources are at an unparalleled premium. Leveraging 25 years of experience in high reliability robotic arms, MDA has developed a suite of miniaturised manipulators to meet these very challenges of planetary exploration, thereby giving rise to the name Exploration Arm.

The Exploration Arm family, in addition to being low mass and highly power efficient, feature scalable and modular designs which can be modified according to the needs of the customer. To date these scalable designs have been considered for systems with up to 6 degrees of freedom, with options for either custom designed, integrated or flight qualified off-the-shelf joint solutions, depending on mass and cost trades. Fig. 12 shows the first Exploration Arm, a 6-degree of freedom manipulator developed at MDA employing off-the-shelf actuators.

Fig. 12. Exploration Arm

To satisfy the needs of the wide variety of surface mission scenarios that will likely face exploration missions over the next decade, MDA's Exploration Arm manipulators are compatible with a range of end effectors, including contact science instruments, regolith scoops, rock abrasion tools, drills and corers. Preliminary scoop designs, for example, at MDA have been parametrically designed to optimize cutting efficiency through a variety of substrates. The scoop can be rotated up to the boom to seal the contents from the environment. Fig. 13 shows one of several scoop designs being ground tested with an Exploration Arm.

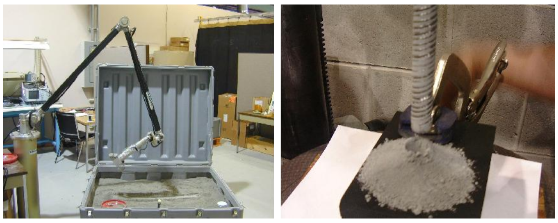

Fig. 13. Exploration Arm Scoop and Drill Bit testing in regolith simulant

MDA has also developed a ground control operator station that places a 3D model of the manipulator in a virtual workspace, updated during each transmission to Earth, based on stereo views from the lander or rover. Trajectories are developed, rehearsed and validated on a terrestrial model and then sent to the vehicle in-situ. Varying levels of autonomy are available to the operators including low-level command scripts, high-level command scripts, and logic branching. MDA's exploration manipulators also have calibrated force sensors to sense forces at the tip and use them as a threshold to stop motion, applying the required preload where necessary.

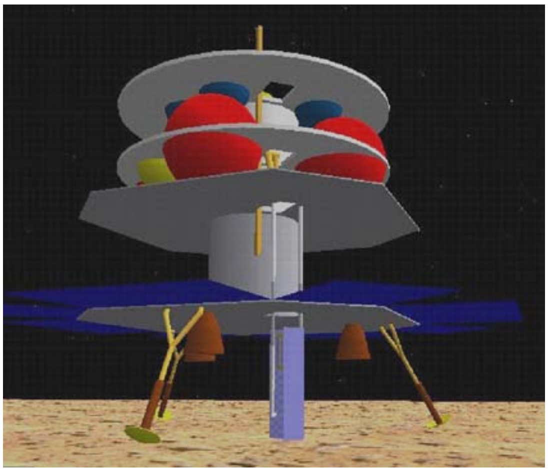

Fig. 14. MDA Concept for the Sample Acquisition, Transfer and Contamination System on ESA's Mars Sample Return (MSR) Mission

Beyond manipulators and into the area of sample triage and processing, MDA developed concepts for the Sample Acquisition, Transfer and Containment System for ESA during the Mars Sample Return Phase A Study (see Fig. 14). The objective of the MSR mission is to return a scientifically interesting Mars soil sample safely to Earth.

MDA has also developed technologies for sample acquisition, sample processing and sample handling under contract to the CSA. Several key technology advancements were made in the areas of drilling/coring (see Fig. 13), sample/core capture, cuttings/fines transport from the bit face, and sample crushing. These technologies are applicable to a wide range of space exploration missions and will enable MDA to play a role in these areas on future programs.

3.6. Spacecraft Rendezvous and Precision Landing

MDA is currently involved in several programs in the area of autonomous spacecraft rendezvous and precision landing (see Fig. 15). MDA was recently selected by NASA to develop precision landing technology with Boeing and the Jet Propulsion Lab under the Human & Robotic Technology (H&RT) program.

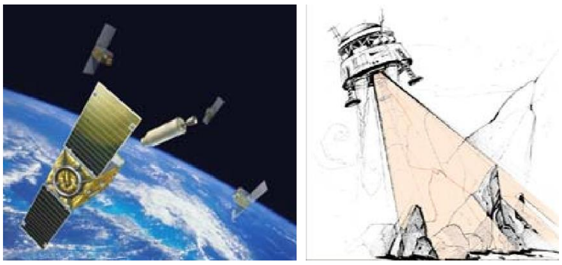

Fig. 15. Autonomous Spacecraft Rendezvous and Precision Landing Concepts

MDA is also leading a team including Optech and NGC Aerospace in the development of lidar-based hazard avoidance technology for planetary landing systems. MDA has recently completed an ESA project to develop control algorithms and simulation models of lidar GN&C for automatic rendezvous and precision landing on Mars.

3.7. Large Structure Manufacture and Assembly

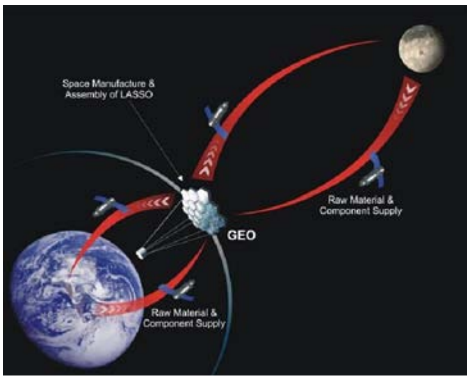

Fig. 16. MDA Concept for Large Structure Manufacture and Assembly

MDA is prime contractor to the US government for the Phase A conceptual development of a large GEO based structure. The focus of the study is to demonstrate on-orbit manufacture and assembly of large structures using terrestrial and lunar raw materials (see Fig. 16). The contract is a follow on study to previous work related to in-situ resource utilization.

3.8. Canadian-led Mars Mission

MDA has completed a study of Canadian-led Mars Missions for the Canadian Space Agency, The mission concept, conceived jointly with Russian subcontractors Lavochkin-Babakin, involves merging off-the-shelf hardware with Canadian science payloads to enable a cost effective Canadian-led Mars Mission. The mission would be led by Canadian scientists and use commercially available launch vehicle and spacecraft technology. Primary mission concepts considered included an orbiter, a rover, and a network of micro-landers (see Fig. 17). .

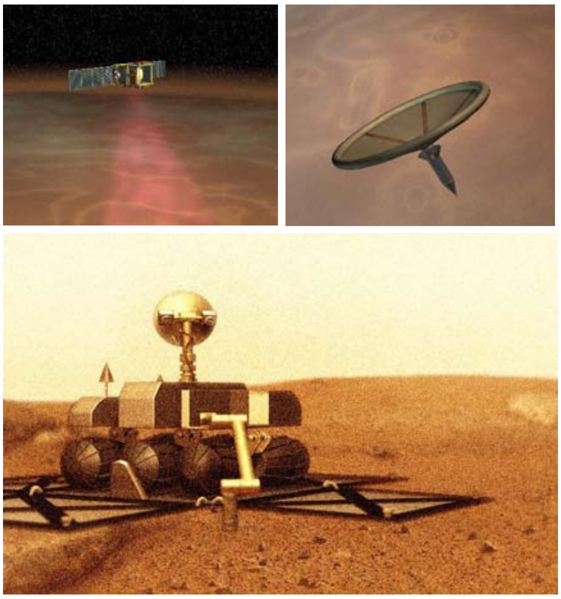

Fig. 17. MDA's Canadian-led Mars Mission Concepts

3.9. Commercial Exploration Missions

It is widely recognised that the future of space exploration is increasingly likely to involve commercial initiatives as well as agency programmes, and MDA has undertaken a number of studies and conceptual development programmes in this exciting area. Commercially funded space exploration missions that have been studied recently have ranged from lunar rover-based entertainment programs all the way to asteroid in situ resource utilisation demonstrations and sample return missions. Fig. 18 shows an example of such a lunar mission study, entirely commercially funded, which leveraged MDA's expertise in rover systems, vision and navigation systems and robotic payload deployment and manipulation systems

Fig. 18. Commercial Exploration Missions

4. CONCLUSION

There is little doubt that over the past three decades Canada has earned the reputation of world leader in orbital space robotics, in no small part due to the exemplary performance of the MDA built SRMS and SSRMS. Indeed these systems have become so widely recognised that they have developed their own household names in Canadarm and Canadarm-2. It is a testimony to the success of these programs that not only are these robotic systems used on virtually every space shuttle flight, but furthermore they have become mission critical elements, as astronaut EVA vehicles and thermal protection system inspection elements.

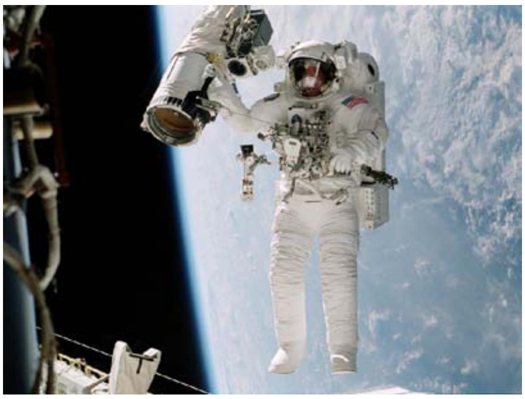

Fig. 19. Astronaut holding on to the Canadarm

This expertise in high reliability, safety critical space robotic technologies has been significantly expanded upon and applied to new and rapidly advancing areas of autonomous satellite rendezvous, docking, servicing, and in-orbit assembly, key enablers in the efforts to expand human and robotic presence into Earth orbit and beyond. MDA is now developing and delivering robotic and autonomous technologies that span almost every phase of planetary exploration missions, from orbital rendezvous, descent and landing, through surface deployment, navigation and control, target selection and characterisation, to surface and subsurface sample acquisition, manipulation, analysis and in situ processing.

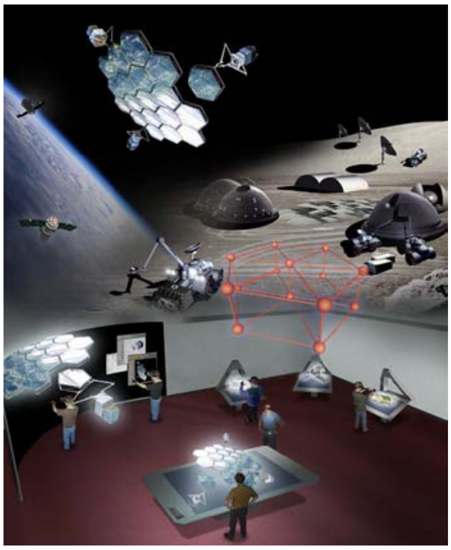

Fig. 20. Robotic technologies spanning the full range of space exploration missions

These strategic technologies will not only allow Canada to continue its leading role in the field of space robotics, but furthermore will provide critical robotic systems for the next chapter in humanity's exploration of space and ensure that Canada is able to play a pivotal role in the endeavour, inspiring and engaging generations for many years to come.