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Recent Canadian Activities in Space Automation & Robotics - An Overview

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Abstract

This paper provides an overview of the Canadian plan for space robotics. The objective of the plan is to explore the new technologies required to enable future space robotics opportunities. The first part of the paper describes the opportunities in MSS operation and evolution, in planetary exploration, and in space servicing. The second part describes current projects in ground control, task verification, advanced design and simulation technologies and planetary exploration.

1 Introduction

Canada has chosen space robotics as one of its key niche areas [1] [2] and is currently delivering flight elements for the main robotic system of the international space station. This program represents an approximate investment of US$ 1 Billion by Canada in the area of space robotics design and development. It follows earlier programs, which led to the design and production in Canada of the highly successful robotic arms for the US Space Shuttle fleet.

The Mobile Servicing System (MSS) is the Canadian contribution to the International Space Station. It consists of three main elements. The Space Station Remote Manipulator System (SSRMS) is a 17-metre, 7-dof, robotic arm used for ISS assembly and payload deployment tasks. The Special Purpose Dextrous Manipulator (SPDM), is a smaller manipulator with two 3.4 metre, 7-dof, robotic arms that can be used independently, or attached to the end of the SSRMS. The SPDM will be used to conduct on-orbit maintenance on the ISS. The Mobile Remote Servicer Base System (MBS) will be used as a support platform and will also provide power and data links for both the SSRMS and the SPDM. The entire Canadian Space Station Robotic System can be seen in Figure 1.

Figure 1: Elements of the Mobile Servicing System

An often-forgotten Canadian contribution to the US Space Shuttle program is the Space Vision System (SVS) being used to assist robot operators during Shuttle flights. Other vision systems are being further developed to enhance the autonomous capabilities of the MSS.

The Canadian Space Agency (CSA), in collaboration with industry, is developing new technologies to fulfil future robotic space mission needs. Canadian capabilities are currently being developed in new design for manipulators, automation of operations, autonomous robotics, vision systems, simulation, robot identification and ground control of space robots.

The CSA is also supporting industries in advanced simulation (contact dynamics, parallelisation) and in 3D vision. These technologies are focussed towards new

space robotics initiatives in space exploration and reusable space and launch vehicle applications.
The first part of the paper describes opportunities for space robotics and the second part describes the current projects in space robotics technology development.

2 Opportunities

Three main areas of space robotics activities have been identified as critical for technology development in the near to medium term: MSS operation and evolution (including Ground Facilities), Planetary Exploration, and Space Servicing.

2.1 MSS Operation and Evolution

Canada is responsible for the sustaining engineering and part of the operations planning of the MSS. Opportunities for enhancement to the MSS and its supporting infrastructure will undoubtedly arise as it enters its operational life. SSRMS and SPDM will likely be required to perform off-nominal operations for which new tools would be required.
One of the capabilities that will eventually be required is teleoperation from the ground. Crew time is a precious re-source and astronauts will be required to perform science experiments on board the ISS. Studies [3] have shown that the crew would not be able to keep up with the routine maintenance demand, much less be able to perform science experiments. The workload imposed on the crew by maintenance operations of the ISS in its current baseline configuration is not yet determined with certainty but the risk remains of overloading very precious human resources with tedious maintenance activities on-orbit.
In addition, enhancements will certainly be made to the ground support infrastructures in order to increase the efficiency of operations planning, verification and training and to incorporate new technologies over the life of the International Space Station. The MSS Operation and Training Simulator (MOTS) will have to be updated to keep up-to-date with technology advances. Smaller but more powerful version of MOTS will be needed. The SPDM Task Verification Facility (STVF) will have to be modified to deal with more complex situations. Modelling and simulation of more complex phenomena like contact dynamics and friction will be required.

2.2 Planetary Exploration

Planetary exploration will represent an important portion of upcoming robotic space missions. Mars is the primary target with many missions planned in the near future: NASA's Mars Surveyor Program is slated to launch missions to Mars every two years in the coming decade. The landers of these missions will perform soil sample collection for in-situ analyses and sample return, as well as executing a wide assortment of astrobiological, geophysical, meteorological and in-situ resource utilisation experiments. Other near term lander missions to Mars include the NetLander program and the Beagle 2 mission. In the medium term, missions to Mars will continue to be launched regularly and robotics will be an enabling technology for most of these missions.
Other planetary bodies in the solar system are also targeted for planetary exploration missions in the near future: the Moon, Mercury and Venus are serious candidates as are some of the moons of the outer planets (Europa and Titan) and the asteroid belt. Private companies are now preparing exploration missions to various places in the solar system such as the Moon and Near-Earth Asteroids. This will pave the way to the commercial exploitation of space resources.
In the long term, human planetary exploration missions to the Moon, Libration Points, and Mars will become a reality. Robots will certainly be required in the early phases of these programs to prepare the arrival of astronauts and they will also be required to assist during the operations phases. Such missions would marry the expertise developed by Canada on planetary exploration missions to that acquired through human spaceflight activities such as the shuttle and Space Station programs.

2.3 Space Servicing

As has been demonstrated by the Shuttle Remote Manipulator System (SRMS) in the past two decades, the added capability and versatility of a payload handling system on an Orbital Vehicle is tremendous. Space servicing capabilities such as precision payload deployment and retrieval, on-orbit construction, EVA support, on-orbit checkout and payload repair have already been performed. Such servicing capabilities and more will be required for future generations of Reusable Launch and Space Vehicles.
As the goal of reducing launch cost to $2,500/kg or less is realised, more commercial exploitation of space is anticipated. Companies such as Space Adventures Inc. are already planning or making reservations for future space tourists. Space-based Solar Power Generation and Space-based production and manufacturing become economically more attractive. Environmental clean up of space debris or re-orbiting of space assets becomes more affordable. All these will call for significant on-orbit infrastructure requiring state-of-the-art space automation equipment.
Given the commercial nature of future Space Servicing applications, it is anticipated that the future on-orbit robotics systems will require higher operational efficiency in an increasingly unstructured work environ-

ment. Furthermore, in many occasions, spacecrafts bearing robotic elements will be unmanned. This will require technologies in autonomous and semi-autonomous operations with as little human-in-the-loop intervention as possible, adaptive robotics interfaces to handle uncooperative payloads and object recognition vision systems. All these would lead to lower cost of operations for any commercial venture. Effective and user friendly simulation tools will needed for the system design and operation to reduce the cost and risks.

Figure 2: Satellite Servicing Concept

3 Current Activities

The Space Technology branch of the Canadian Space Agency, MD-Robotics and other Canadian industries are currently involved in projects to open new opportunities for space robotics. Active research is currently being pursued in the following areas:

- Vision Systems for Space,
- Ground Control of Space Robot,
- SPDM Task Verification Facility,
- Advanced Design for Robotic Systems,
- Advanced Simulation Tools,
- Activities in planetary exploration.

3.1 Vision Systems for Space

Canada has recognised the importance of vision system technology as a key enabling technology required for space robotics operations and initiated several development activities including: Space Vision System (SVS-NEPTEC), Laser Camera System (LCS-NEPTEC), Object Recognition and Pose Estimation Toolkit (ORPE – MD-Robotics), CSA Laser Range Scanner (LARS), and others.

The LCS is an eye-safe laser scanner capable of tracking targets or imaging objects up to several meters away. It uses the auto-synchronous scanning principle developed by the National Research Council of Canada [4]. The LCS has been delivered to NASA (Figure 3) and will be flown as a Development Test Objective (DTO) on board the NASA Space Shuttle Discovery on the ISS Assembly Flight 7A.1 in July 2001. This system will provide a versatile, robust vision system that can function in any kind of lighting condition normally encountered in the space environment. The system will incorporate video (SVS), laser ranging and imaging capability. In imaging mode, LCS produces data can be processed by off-line software to produce 3-D images or to make quantitative measurements.

Figure 3: The Laser Camera System (LCS) from NEPTEC

ORPE (Figure 4) is a stereo vision system that allows recognition and pose estimation and tracking of objects in space, based solely on the natural features of objects, without the need for specific visual targets attached to them [5].

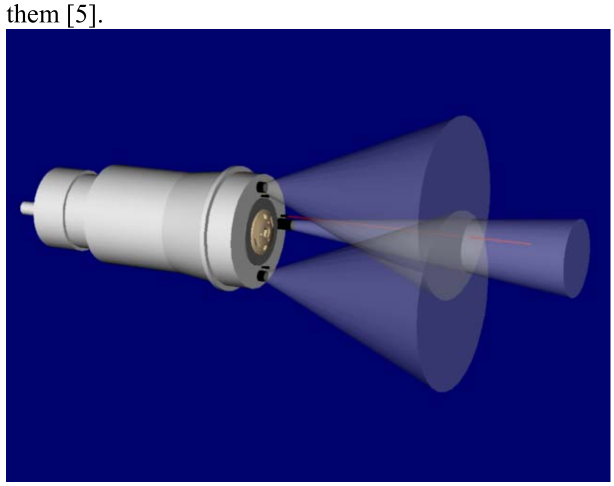

Figure 4: Concept for ORPE

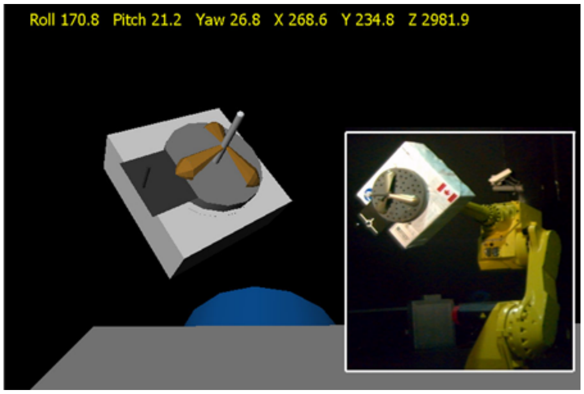

Figure 5: Object Tracking with 3D Vision Tracking System ORPE

The CSA has supported the development of vision systems for space (SVS, ORPE, LCS, LARS) and continues to support this effort through contracts and in-house research. Internally, CSA has undergoing research with the auto-synchronous laser (LARS) including time of flight ranging (lidar) [6] and stereo-vision and the combination of such systems.

3.2 Ground Control of Space Robots

For most upcoming space robotics applications, there will be a need to safely control and monitor operation from Earth-based stations.

The Canadian Space Agency in partnership with the Deutsche Zentrum für Luft und Raumfhart (DLR) and MD-Robotics has embarked on a technology demonstration program to validate the concept of ground operations for the MSS. The near-term objective of the program is to evaluate various ground control technologies and to perform a preliminary validation using a representative simulation environment: the MSS Operations and Training Simulator (MOTS).

Two projects are being led in parallel to allow for a comparison of different approaches. The first is an adaptation of DLR's Modular Architecture for Robot Control (MARCO), a ground segment derived from that of the highly successful ROTEX mission. MARCO has also since been used for the remote commanding of the robotic arm on NASDA's ETS-7 satellite [7]. The second project is done in collaboration with MD-Robotics and involves an adaptation of the Intelligent Interactive Remote Operations (IIRO) architecture [8][9]. This architecture was used to demonstrate in 1999 the remote control via Internet, from the CSA headquarters in St-Hubert, of a robotic excavator located in Edmonton, Alberta (approx. 4000 km distant) and a robotic arm located at MD Robotics in Brampton Ontario (500 km distant). These systems are currently being adapted to the capabilities and limitations associated with the MSS and ISS operations.

The objective of this research program is to lead to a Station Development Test Objective where the control of the real MSS hardware would be performed from a ground station. Conducting tests in a systematic and rigourous manner will help validate the concept of MSS ground operations and pave the way for the implementation of such a capability in the ISS program.

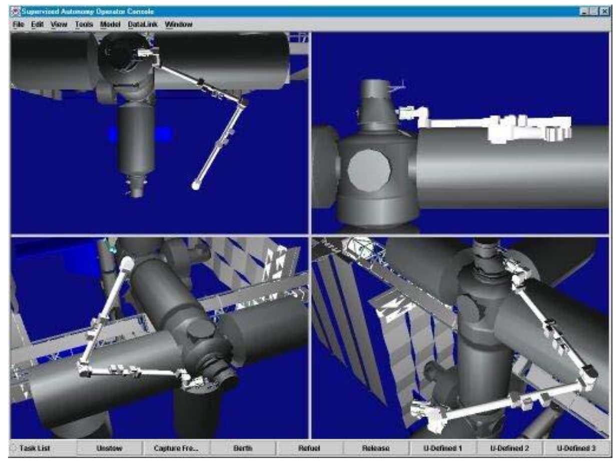

Figure 6: MSS Ground Control Station User Interface

For applications requiring more autonomy such as unmanned reusable space vehicles (RSV) and planetary exploration missions, the CSA, MD-Robotics and the University of Toronto are also collaborating on a project entitled Remote Operations with Supervised Autonomy (ROSA) [10]. The objective of this project is to investigate technologies that will lead to more autonomous operations than what is considered for MSS. Key components of this project are the development of a variable autonomy architecture that can be reused for different applications, and of vision sensing algorithms to provide environmental information to a local decision-making engine that is responsible for conducting the mission.

3.3 SPDM Task Verification Facility (STVF)

The cost and risks associated with the execution of robotic tasks in space require that all procedures be verified on earth prior to their execution in space. Canada is responsible for the verification of all the tasks involving the SPDM. The Canadian Space Agency (CSA) is currently developing the SPDM Task Verification Facility (STVF). It consists in a series of simulation and analysis tools to be used for verifying the kinematics (clearance, interface reach, degrees of freedom), dynamics (insertion forces, flexibility), visual accessibility (ability to see the work site) and resource allocations (power, crew time).

One of the main technical challenges with the STVF is the verification of the feasibility of the insertion/extraction tasks. The forces involved are mainly the result of complex frictional contact between the payload and the work site. Accurate parameters for contact models are difficult to obtain, especially since friction parameters are inherently different in laboratory and in space. Another important requirement for the STVF is the capability to verify if the selected procedure provides sufficient visual cues on the payload and work-site. The SPDM operator will rely exclusively of camera views for executing the task, and must be able to see properly the edges of the payload and work-site. Although simulating the right surface finish, lighting conditions and camera characteristics in software is feasible, hardware validation is still required.

The concept of the STVF is shown schematically in Figure 7. It can be split into three main components: a real-time simulator called the MSS Operation and Training Simulator (MOTS), a hardware-in-the-loop simulator called the STVF Manipulator Testbed (SMT) and a non real-time simulator called the Manipulator Development and Simulation Facility (MDSF-NRT).

Each component of the STVF is used to fulfil a particular objective in the verification process. A session on the MOTS real-time simulator essentially verifies the task execution in its entire scope, including malfunctions and operator interface. For the verification of criteria relying on the less reliable real-time simulation model, such as contact dynamics and visual environment, the real-time hardware-in-the-loop simulator (SMT) is used. Finally, the detailed verification of the effect of parameter tolerances on the contact behaviour is performed using the MDSF-NRT.

The STVF Manipulator Test-Bed (SMT) is a hardware-in-the-loop simulator and constitutes the main addition to current CSA facilities. It is used to verify the contact dynamics behaviour and the visual aspect of SPDM tasks in the immediate vicinity of the work site. The SMT is composed of five major items: the SMT operator and controller stations, the simulator, the robot, the ORU/work site mock-ups, and the visual environment. The robot shown in Figure 8 is a high precision hydraulic manipulator with a payload capacity of more than 100 kg developed for CSA by International Submarine Engineering.

In the SMT concept, the simulator mimics the dynamic response of the SPDM, submitted to end point contact forces and operator commands. Its response drives the SMT robot end-effector motion to replicate the simulated SPDM motion. Mock-ups of the ORU and work-site are used to emulate the contact interaction occurring during the task. The measured contact forces are fed back to the simulator that, in turn, simulates the response of the SPDM to the measured force [11][12].

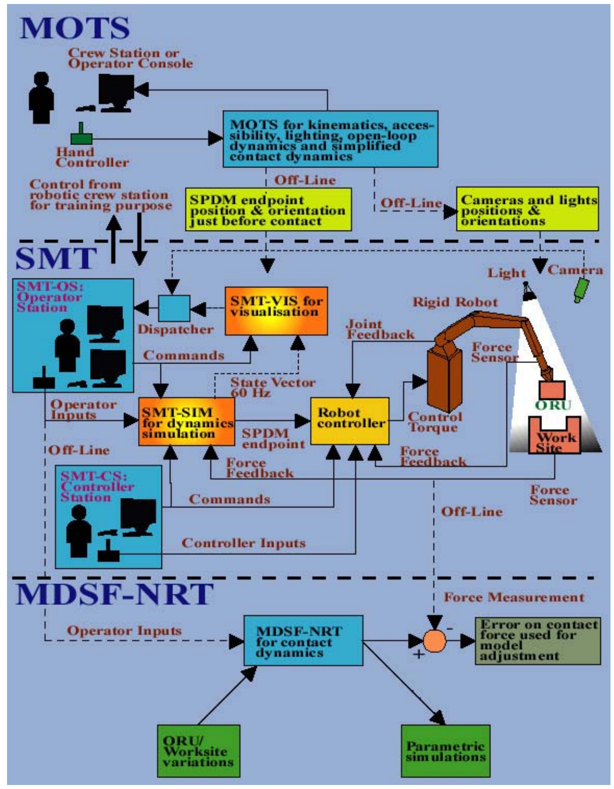

Figure 7: Validation of Space Robot Tasks on Ground

Figure 8: STVF Manipulator

3.4 Advanced Design for Robotic Systems

ARMS Project

The availability of technologies that enable very low mass, low cost solutions for smaller robotic arms is very important for Space Exploration and Space Servicing applications. To this end MD Robotics has initiated a number of advanced technology projects to explore and further develop emerging technologies. One such project is the Advanced Robotic Mechatronic System (ARMS).

In this project, emerging technologies such as laser consolidation, ultra-sonic motors and which speed data buses will be explored. Laser Consolidation has been developed by the National Research Council of Canada [13]. It permits the direct manufacture of metal (aluminium, steel, titanium etc.) components directly from Computer Aided Design (CAD) drawings. It is anticipated that the Laser Consolidation technology will permit the manufacture of complex piece parts with very rapid manufacturing turn around, unlike conventional machining which may require many weeks. This manufacturing process will yield parts with tolerances better than 0.03 mm and surface finishes to the micrometer range.

The ARMS project also investigates the use non-conventional actuation technologies such as piezo-electric ultrasonic motors for future robotic missions. The main advantages of such motors are their compactness, high torque-to-mass ratio and non-backdriveability. Their main disadvantage is a relatively short and badly characterised life cycle.

The ARMS project will also integrate a high speed (circa 2 gb/s) serialised data bus with nodes at each joint or key interface which will permit the control of all joints and interfaces and sensors by a centralised controller. With sub microsecond communications latency, this centralised controller may provide the joint motor control directly thereby eliminating the need for multi-wire cable harnesses and microprocessors at joints etc. This architecture is expected to save some 20% of system weight and approximately 40% of system power (no need to heat sensitive electronics). Standardised nodes will provide the protocol communication and the reporting of the node's health status. This system will be required to provide self-diagnosis and provide 100% availability with up to 2 failures. The data bus is a joint CSA MD Robotics development.

One of the aims for the ARMS project is the elimination of all processing and sensor electronics from the robotic arm and the location of such electronics at the centralised processor. This will make the robotic arm much lighter and smaller and will only require protection of the central processor from the environment.

SARAH

SARAH (Figure 9) is a self-adaptive and reconfigurable robotic hand for space applications which is versatile, robust and easy to control. This hand has three fingers and each of the fingers has three phalanxes. The self-adaptability of the hand is obtained using underactuation within and among the fingers. Underactuation between the phalanxes of a finger is realised using linkages and springs while the underactuation among the fingers is implemented by a special one-input/three-output differential. An additional degree of freedom is used to rotate two of the fingers in order to reconfigure the hand and fit the general geometry of the object to be grasped. Overall, the hand has ten dofs, actuated by two motors, i.e., one for opening/closing of the fingers and one for orienting the fingers. In a specific application, the robotic hand is a passive tool and the actuation is provided by the socket torque of an ORU Tool Change Out Mechanism (OTCM).

Figure 9: SARAH Hand

3.5 Advanced Simulation Tools

MSS Operation and Training Simulator

To support the operations and utilisation of the MSS, the CSA is providing a ground segment. The MSS Operations and Training Simulator (MOTS), developed by CAE Electronics, is a key element of this ground segment, providing real-time simulation of the MSS and its environment to support operations, development, and training [14].

MOTS is a state-of the art simulator providing astronauts with a simulation representative of the Space Station environment through creation of the on-orbit dynamic and visual environment (Figure 10). MOTS provides sufficient real-time high-fidelity simulation of the flexible dynamics performance of two robotic arms concurrently in a micro-gravity environment to support complex "hand-off" tasks in addition to single manipulator activities. Contact dynamics models (described in the next section) enhance the realism of berthing payloads to the Space Station with multiple contact points simultaneously tracked. 3D visual models support realistic views generated from MSS camera models in an operational and dynamic lighting environment that includes the production of split screen views. The incorporation of the Space Station Robot Arm Flight Control System Software provides an invaluable and trusted environment in which on-orbit tasks can be planned and practised. MOTS is also being integrated into several facilities at the Canadian Space Agency such as the SPDM Task verification Facility (STVF) and the Space Operations and Support Centre, which will be driven with telemetry data from the MOTS.

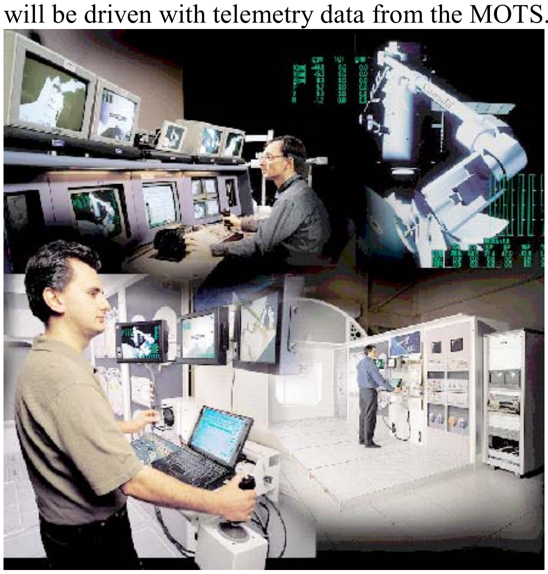

Figure 10: MSS Operation and Training Simulator (MOTS)

Contact Dynamics Modelling and Simulation

The Contact Dynamics Toolkit (CDT) is a self-contained software library developed by MD Robotics for the modelling and simulation of intermittent contact/constrained dynamics of mechanical bodies [15]. The CDT has been and is instrumental in the development and verification of the robotic manipulator systems developed by Canada for the assembly and maintenance of the International Space Station. The CDT is also becoming a technology discriminator for Satellite Docking and Capture Systems.

The CDT applications (current and potential) are:

- ISS assembly, using SSRMS
- Payload hand-over from SRMS to SSRMS
- Replacement of faulty ORUs on the ISS by the SPDM
- Assembly/maintenance of the Japanese module on ISS, using JEM
- XEUS assembly, using ERA
- Docking to the ISS
- Satellite docking and servicing

With the CDT as its kernel (and modelling the contact regime), a Simulink-based satellite Docking Simulator is being developed to support feasibility studies and design, development and verification of satellite docking and capture systems (Figure 9). Using this tool, it will be possible to optimise the design of docking systems by adjusting the geometry of the contact interface, the friction/stiction of the contacting surfaces, the properties (stiffness and damping) of the docking device compliance, etc. A complete analysis in the presence of positional misalignments and relative velocities between the target and the chaser satellites will also be feasible using this simulator.

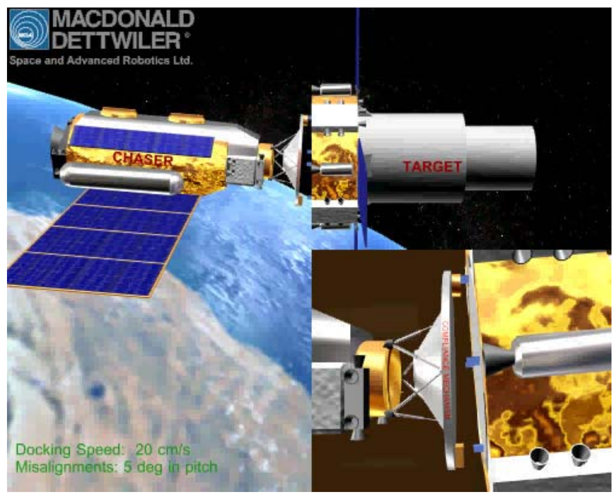

Figure 11: Satellite Docking Simulator Developed by MD-Robotics

SYMOFROS

SYMOFROS is a modelling and simulation tool developed at the CSA initially for R&D and which is now used to support operations. Its main characteristics are the generation of the model using symbolic approach, its connection to Matlab/Simulink for simulation and its ability to generate real-time code using Simulink RTW. This code can be parallelised on a computer cluster using the RT-LAB product of Opal-RT. SYMOFROS is the main tool used to develop the real-time controller of the STVF manipulator. It is also used to develop a generic simulator for astronaut training for classroom exercise and has been used in a few university projects.

The current developments on SYMOFROS have the following objectives:

- Continue to improve the real-time capabilities
- Improve the closed kinematics loops capabilities
- Generate efficient code using parallelisation at the dynamics model level
- Interface SYMFROS with the CDT to create a satellite-docking simulator in collaboration with MD Robotics.

BORIS

The space agencies involved in the ISS program have the mandate to provide a Generic Robotic Training course. CSA has developed a new simulator called Basic Operational Robotic Instructional System (BORIS). This simulator is used to introduce generic robotics concepts to operators under training [16].
The simulator provides a 6 degrees-of-freedom robot that includes in-line and offset joints. According to the lesson level, the instructor can select a robot with rigid or flexible links and elastic joints. The robot is located in a virtual cargo terminal in space, called Spaceport. The robot handles payloads attached to standard palettes. The operator's main objective is to capture the palettes and move them into Spaceport's docking modules. Figure 12 presents the view provided by two Spaceport's cameras (top and right view) and the tip camera (left view). The operator can also use virtual reality in order to be immersed in the Spaceport’s environment and to inspect the robot.

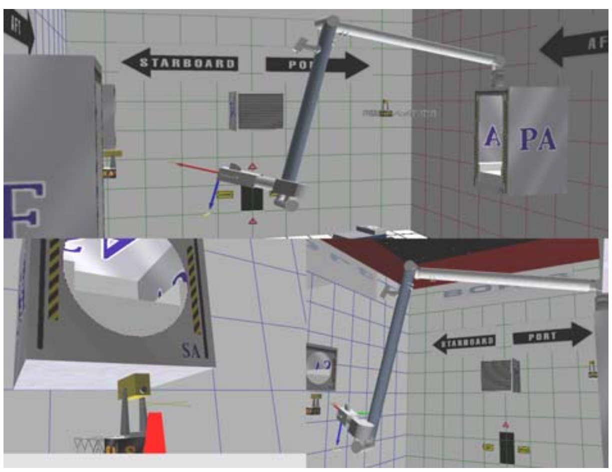

Figure 12: BORIS Simulator for Generic Training

3.6 Planetary Exploration

Canadian Space robotics expertise has recently been expanding with the development of small, lightweight, low-power, low-cost robots that are capable of operating in harsh planetary environments. This was sparked by a strong interest from the Canadian planetary science community to explore Mars, the Moon and other bodies in our solar system.

Mars Missions

Under the now-defunct Mars Sample Return 2003 and 2005 programs, Canada had expressed interest in providing an arm for the manipulation of scientific instruments and payloads. Since then, the CSA has been approached by numerous planetary scientists from all over the world eager to use such a capability.

As a response to the enthusiasm of the scientific community, a contract was given to MacDonald Dettwiler Space and Advanced Robotics to perform a feasibility study for the development of a manipulator for future Mars missions [17]. This study was conducted before the cancellation of the MSR 2003 and 2005 missions. These two missions had then been used to derive a set of requirements for a lander-based manipulator. Typical tasks to be performed by such a manipulator included deployment of scientific instruments and sample acquisition. This study provided a conceptual design for a manipulator including its end-effector, drive electronics and terrestrial ground segment.

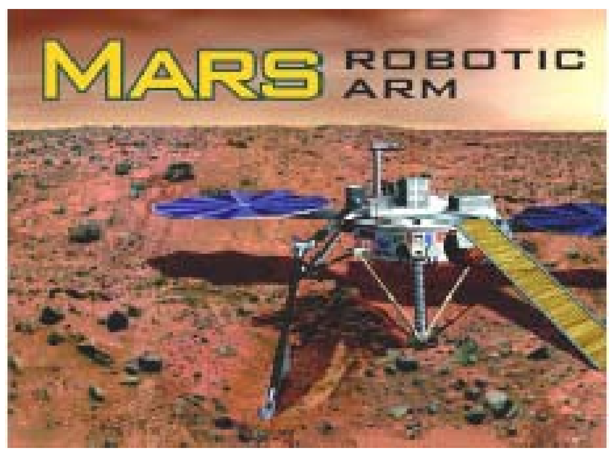

Figure 13: Mars Robotics Arm

A program is currently under way for the development of a demonstration unit for functional testing using requirements similar to those of the feasibility study. The output of this program will be a demonstration arm using the same technologies as would be necessary for manipulation of scientific payloads on the surface of Mars. The intent of the study is to provide and demonstrate a design that will work for a known planetary environment and flexible enough to be adapted to meet the requirements of missions on different planetary bodies.

Drilling

Another interesting development in planetary exploration comes from the Canadian mining industry, which is a recognised world leader in mining automation. A consortium of Canadian mining companies, headed by the Northern Centre for Advanced Technology (NORCAT) is presently working on the development of a diamond core drilling apparatus for extra-terrestrial subsurface resource utilisation [18]. Current efforts are focussed on the adaptation of mining technologies to space operations, in particular Mars and Near Earth Asteroids.

This core drill (Figure 14), which will have the capability to extract core samples at depths up to 100m, has raised a lot of interest in the international community. It will allow subsurface exploration of planetary bodies and is paving the way for planetary exploitation in the coming century.

Figure 14: Core Drill Developed by NORCAT

Spherical Robot

The University of Sherbrooke is working on an innovative locomotion concept that could be used in planetary exploration. Wheeled robots have limited mobility capabilities and special care must be taken to avoid having them flip over when moving on an uneven terrain. Figure 15 presents the concept of a spherical robot that moves by making its external shell rotate. The spherical shape allows the robot to operate on all kinds of operating surfaces and obstacles. The characteristics and capabilities of such robot are presented in [19], along with some ideas on how such design can be beneficial for planetary exploration. For instance, having the robot encapsulated in a shell protects the circuitry against shocks, dirt, thermal variations and other environmental effects that electronic devices are sensitive to.

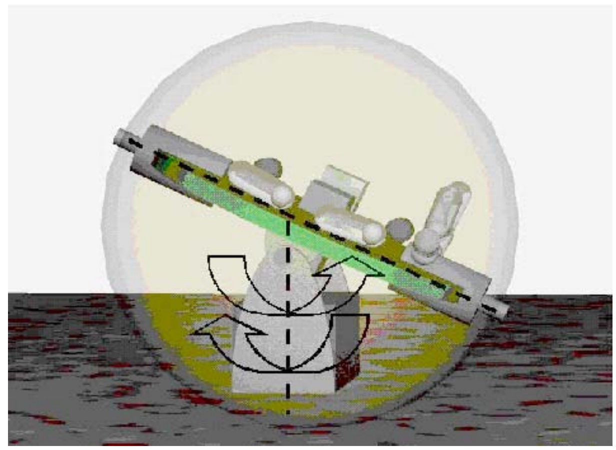

Figure 15: A Spherical Robot for Planetary Exploration

Network of Robots

Finally, the University of Toronto Institute for Aerospace Studies is developing a concept network of autonomous mobile robots intended to carry out tasks related to planetary space exploration [20]. This facility consists of six mobile robots which communicate with each other and a central computer through radio communications. Figure 16 shows the six mobile robots of the RISE (Robotics In Space Exploration) Network. The focus of RISE is on the autonomous control of such a network. Each robot has its own local computing facilities yet the group must work together to accomplish the types of task that would be necessary for network science. This is achieved using decentralized behaviour-based controllers interacting through radio communications. A centralized controller is not required but the central computer can be used to issue high-level commands (e.g., start, stop, pause) or upload/download information from the robots. By designing the system to be completely modular, a high level of redundancy has been achieved. If a small fraction of the robots malfunction, the system is able to carry on with the mission undeterred.

Figure 16: Mobile robots making up the RISE network

3.7 CART Experimental Testbed

To assist in the development of strategic technologies, technology demonstration/validation and training, CSA has developed the Canadian Space Agency's Automation and Robotics Testbed (CART) in collaboration with many Canadian companies (Figure 17). CART is a dual-arm redundant robotic system consisting of two seven degree-of-freedom manipulators. Additional components include a specialised gripper, a three-fingered hand (SARAH), 3D vision systems, collision detection system, real-time system development, and advanced control algorithms.

Figure 17: CSA Automation and Robotics Testbed (CART)

CART is currently used to provide training to astronaut and to develop advanced force control techniques. Among other projects are:

- Vision-based autonomous control using a 3D vision system;
- Control of the three-finger SARAH in conjunction with the 3D vision;
- Free floating object capture;
- Test bed for ground control of space robots;
- Computer system dependability.

4 Conclusion

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 will provide sophisticated hardware as the main robotic system to be used for the construction and operation of the International Space Station. Strategic robotic technologies are being developed in industry and at the CSA to allow Canada to continue as the space robotic leader. The current technology base is being enhanced to enable Space Station operation, evolution and robotic science experimentation. In addition, significant robotic technologies are currently being developed in Canada targeted specifically at solar-system exploration, plus next-generation launch and space vehicles.

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