Proceeding of the 7th International Symposium on Artificial Intelligence, Robotics and Automation in Space:
i-SAIRAS 2003, NARA, Japan, May 19-23, 2003

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 on-orbit 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. Through these investments, Canada is leading the activities in on-orbit servicing and assembly using robots.

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), the Canadarm2, is a 17-metre, 7-dof, robotic arm used for ISS assembly and payload deployment tasks. It has been launch in Spring 2001 and it is now the space manipulator with the longest flight time. The Mobile Remote Servicer Base System (MBS), now installed, is used as a support platform and also provide power and data links for both the SSRMS and the SPDM. 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 entire Canadian Space Station Robotic System can be seen in Figure 1.

Figure 1: Elements of the Mobile Servicing System

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 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 On-Orbit 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 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 have shown that the crew will not be able to keep up with the routine maintenance demand, much less be able to perform science experiments. For certain operations, performing maintenance tasks using the SPDM will reduce the workload by 50% compared to EVA operations. However, despite these gains, it is estimated that astronauts will spend approximately 1600 crew-hours per year performing robotic operations in addition to the EVA hours required for maintenance. The Canadian MSS program is currently working on developing the capability to operate the MSS from the ground to free up crew hours for science purposes.

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. 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 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. Near term landed missions to Mars include the Mars Exploration Rovers and the Beagle 2 lander. In the medium term, the Mars Science laboratory mission will perform a wide variety of science on the surface of Mars and will necessitate many robotic elements.

Other planetary bodies in the solar system are also targeted for planetary exploration missions in the mid-term: 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 On-Orbit 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 using Canadian technologies. 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 Orbital Recovery Inc. are already planning to offer extended satellite life by sending a new thrusters unit that will connect to the satellite. 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 environment. Furthermore, 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 be needed for the system design and operation to reduce the cost and risks.

Figure 2: Satellite Servicing Concept

3 Current Activities

The Canadian Space Agency and the Canadian industry 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,
- Planetary robotics.

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), LIDAR sensors for Entry-Descent and Landing as well as for orbital rendezvous (LAPS and RELAVIS by Optech/MD-Robotics), 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 has 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 provides a versatile, robust vision system that can function in any kind of lighting condition normally encountered in the space environment. The system incorporates 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 stereovision 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].

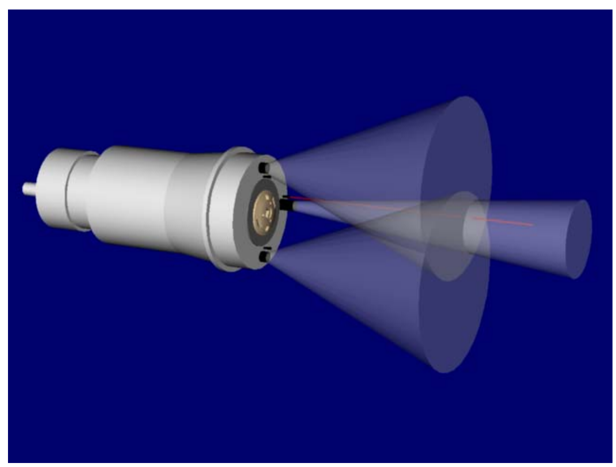

Figure 4: Concept for ORPE

In preparation of its Mars exploration program, the CSA has funded the development of a LIDAR sensor for the detection of hazards during the terminal descent phase for Mars landing missions. This sensor, developed by Optech is also usable for orbital rendezvous applications in Earth or Mars orbit. It has a scan rate of several kHz (depending on the application), its accuracy is on the order of 1 cm and its range can extend from less than one meter to several kilometres. Currently, the application of LIDAR sensors to rover navigation is also being investigated. Figure 6 shows a point cloud obtained by scanning an Envisat mockup using a commercial-grade lidar. This data is typical of what could be obtained from a lidar sensor in the LAPS or RELAVIS system.

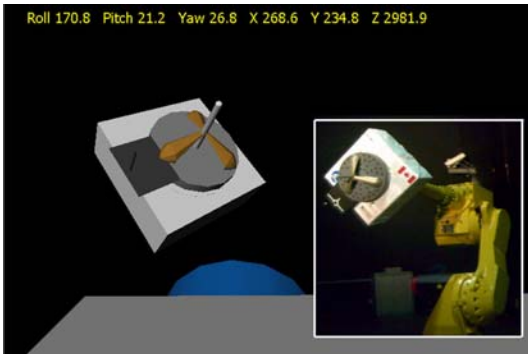

Figure 5: Object Tracking with 3D Vision Tracking System ORPE

The CSA has supported the development of vision systems for space (SVS, ORPE, LCS, LAPS) 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 stereovision, and the combination of such systems.

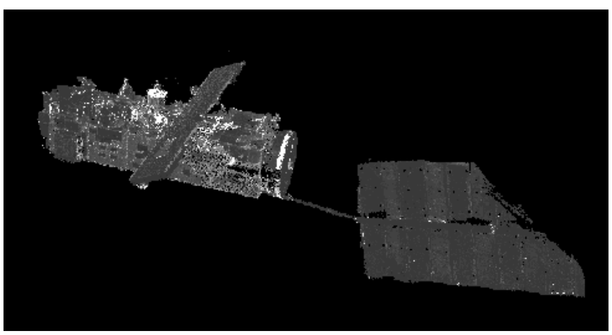

Figure 6: Lidar Scan of Envisat Mock-up

3.2 Autonomous Robotics and Ground Operations

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 have validated the concept of ground operations for the MSS using a representative simulation environment: the MSS Operations and Training Simulator (MOTS). Following this demonstration, the CSA is currently working on incorporating ground control as a basic capability for the MSS. This will be necessary to reduce the workload of the crew on-orbit during the maintenance phase of the ISS.

A first demonstration involved an adaptation of DLR's Modular Architecture for Robot Control (MARCO), a ground segment derived from that of the highly successful ROTEX mission [7]. As a comparison, the Intelligent Interactive Remote Operations (IIRO) architecture [8][9] was also adapted for MSS operations.

The next step in this program is the development of a Station Development Test Objective where the control of the real MSS hardware will be performed from a ground station.

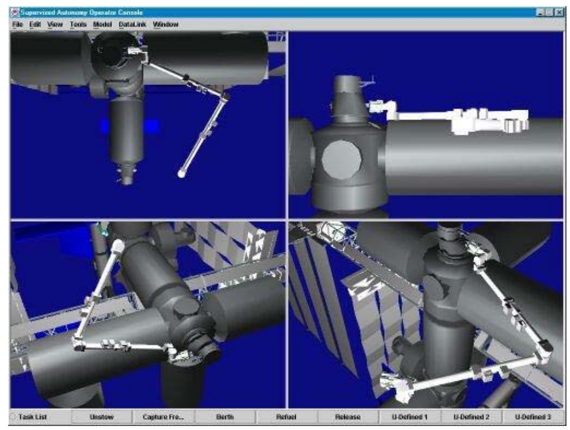

Figure 7: MSS Ground Control Station User Interface

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].
As a follow-on to the ROSA project, the CSA is working on a next generation software architecture for Autonomous Robotics and Ground Operations. This software, named ARGO, will build on the best elements from the MARCO, MGOPS and ROSA software and incorporate them into a modular architecture that will allow provide a generic ground control station for space robots with varying autonomy needs. Applications will range from MSS operations, which require little autonomy, to satellite servicing and planetary exploration using robotic rovers.

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. The Canadian Space Agency (CSA) is currently completing the SPDM Task Verification Facility (STVF). It consists in a series of simulation and analysis tools to be used for verifying the kinematics, dynamics, visual accessibility and resource allocations.

One of the main technical challenges with the STVF was 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.

The concept of the STVF is shown schematically in Figure 9. The verification is 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).

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].

3.4 Advanced Design for Robotic Systems

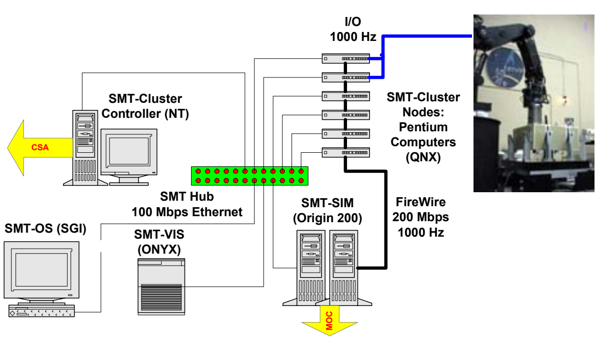

Figure 8: STVF Manipulator Testbed

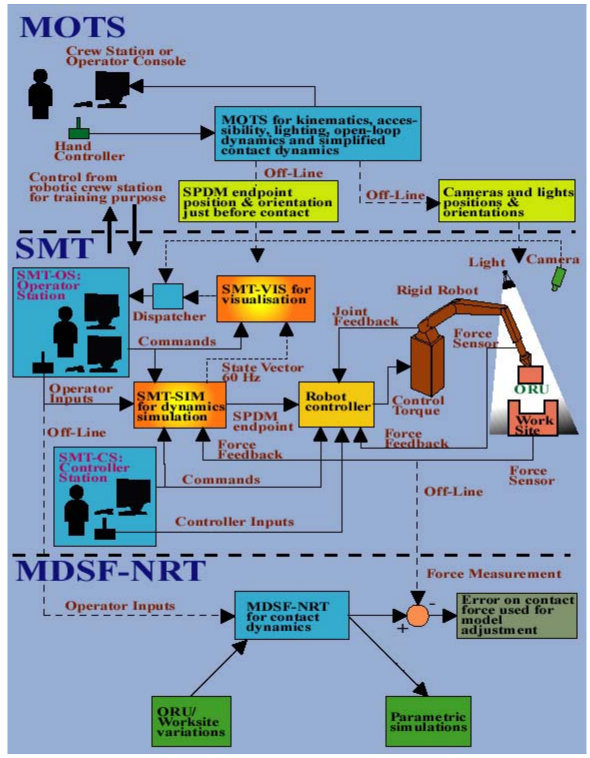

Figure 9: Validation of Space Robot Tasks on Ground

High-Speed Databus

Development of a high-speed (circa 2 gb/s) serialised data bus with nodes at each joint or key interface that 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. A first version (Figure 10) of the bus card developed by Xiphos has been flown on both a microsat mission and on the ISS.

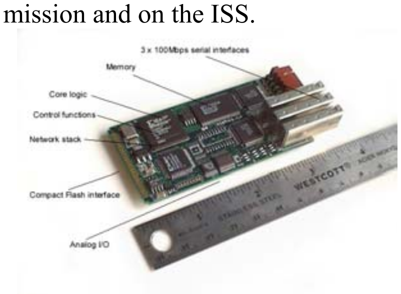

Figure 10: Xiphos Card for Databus

SARAH

SARAH (Figure 11) 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. 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. For the specific application with SPDM, the robotic hand is a passive tool and the socket torque of the ORU Tool Change Out Mechanism (OTCM) provides the actuation.

As compared to other robotic hand SARAH is simpler and hsa fewer degrees of freedom. However, from a practical point of view the additional degree-of-freedom are not required to replace an astronaut with gloves. In fact, recent operational studies have been conducted to demonstrate the suitability of SARAH to manipulate some of the same objects as astronauts such as handrails, thermal blankets or ISS camera poles. The simplicity of SARAH will simplify the space qualification. The planning for a space demonstration of the SPDM version is underway to show the capability of SPDM to perform astronaut tasks. Another potential mission considered is grasping a satellite in an on-orbit servicing scenario.

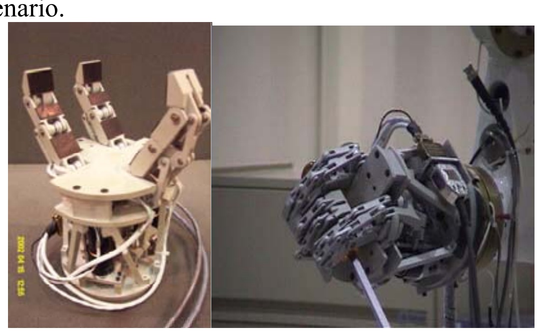

Figure 11: SARAH Hand

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 12).

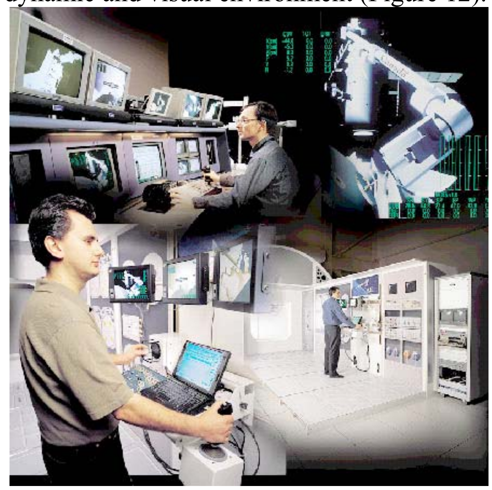

Figure 12: MSS Operation and Training Simulator (MOTS)

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.

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 is 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 is also be feasible using this simulator.

The CDT has been incorporated in the Symofros environment (described below) and is currently being validated using the STVF manipulator with one of the SPDM payload. This will be one of the most extensive validations of a contact dynamics simulation.

In parallel, we are investigating new technique for contact dynamics modelling and simulation. A promising avenue is the computation of the contact force based on the interference volume in a model based on local compliance. Another avenue is the combination of rigid body approach using unilateral constraint with a local compliance model.

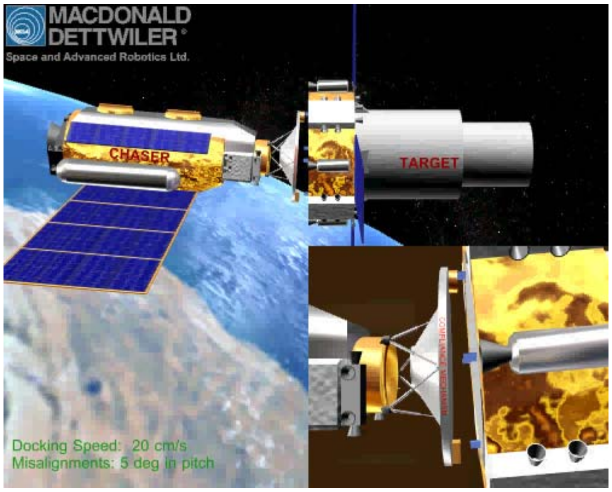

Figure 13: Satellite Docking Simulator Developed by MD-Robotics

SYMOFROS

SYMOFROS is a modelling, simulation and real-time controller implementation environment developed at the CSA. As shown in Figure 14, its main characteristics are the generation of the model using symbolic approach, its connection to Matlab/Simulink for simulation, its ability to generate real-time code using Simulink RTW and its library for real-time control. The generated C-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 and is being used in a few university projects. Symofros is available freely for R&D.

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
- Include real-time contact dynamics capabilities using MD-Robotics CDT but also in-house develop advanced contact models.

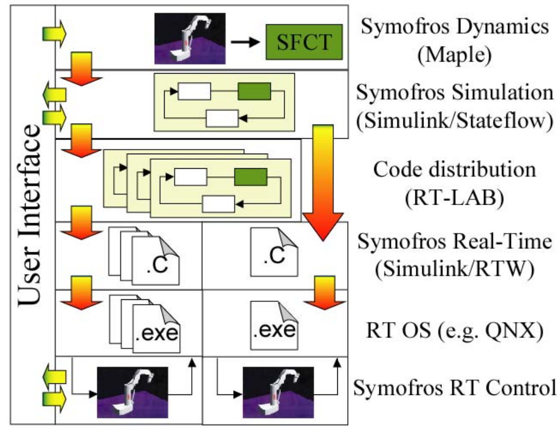

Figure 14: The Symofros Environment

On-Orbit MSS Training Simulator

Experimental tests and analysis have shown that the capture of free-flyers is the most complicated task to be performed by a robotic operator on board of the International Space Station (ISS). The understanding of Canadarm2 and free-flyer dynamics require highly qualified and well-trained operators. The dexterity and accuracy of the astronauts may de-crease over time if they are not trained on-board. It was an obvious choice to have a simulator on-orbit to keep the skills of the astronauts at the required level. In order to support the training scenarios required by the on-orbit training, the System for Maintaining, Monitoring MRO Performance on board the ISS (SMP) simulator has been developed. The main objective of the simulator is to determine if an astronaut is ready to perform an operation with the real Canadarm2. The training scenario, implemented in the SMP, consists of capturing a free-flyer with the Canadarm2 as shown in Figure 15.

This real-time simulator is running on a IBM 800 MHz latop. The hand controllers are connected using the Xiphos card described above. The real-time modeling and implementation is done using Symofros. The Canadarm2 flexible model has been validated using flight data. The experimental system was launched in February 2003 and will be used by several astronauts and cosmonauts.

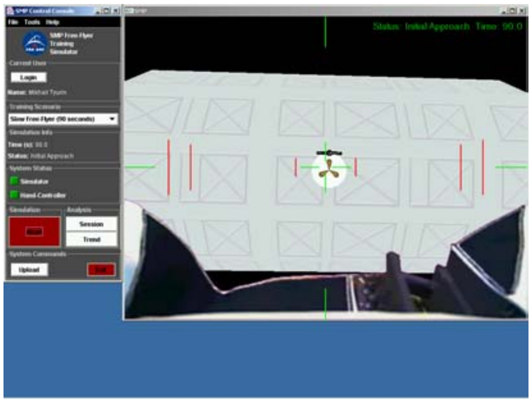

Figure 15: The SMP Simulator

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

To prepare Canada for a participation to potential mars missions, a contract was awarded to MacDonald Dettwiler Space and Advanced Robotics for the development of a manipulator for future Mars missions [16]. 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.

A demonstration arm has been developed using requirements similar to those of the feasibility study and has undergone functional testing. The lessons learned from this study will serve for the development of other mechanisms for Mars exploration and will provide and demonstrate a design that is 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) has developed a diamond core drilling apparatus for extra-terrestrial sub-surface resource utilisation [17]. Current efforts are focussed on the adaptation of mining technologies to space operations, in particular Mars and Near Earth Asteroids.

Figure 16: Mars Robotics Arm

This core drill (Figure 17), which has the capability to extract core samples at depths up to 10 m, has raised a lot of interest in the international community. It has undergone a test campaign to demonstrate the feasibility of the concept for space application. The testing involved drilling through 2.1 meters of a mixture of hard rock, sedimentary rock and regolith. The drill successfully penetrated all materials with penetration rates and power levels compatible to what could be expected on a Mars mission.

This drill will allow subsurface exploration of planetary bodies and is paving the way for planetary exploitation in the coming century. A new prototype of a one-meter class drill is currently under development for mobile planetary drilling applications.

Figure 17: Bit of Core Drill Developed by NORCAT after testing

Network of Robots

The University of Toronto Institute for Aerospace Studies (UTIAS) is developing a concept network of autonomous mobile robots intended to carry out tasks related to planetary space exploration [18]. This facility consists of six mobile robots which communicate with each other and a central computer through radio communications. Figure 18 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.

To broaden the scope of planetary exploration research, the UTIAS is proposing to set up a research network on Autonomous Robotics for the Exploration of Space (ARES). The centerpiece of the ARES network would be a Mars emulation facility, coined MarsDome, to be used to simulate Mars exploration missions.

The next generation of laboratory rovers to be used for the development of network science technologies have been produced. These new rovers are now capable of traversing terrain typical of outdoors environments and will increase the relevance of the research to planetary missions.

Mobile Robot Autonomy

Finally, the Canadian Space Agency has started an in-house development program to adapt its state-of-the-art developments in ground operations and autonomous robotics to mobile robots in a planetary exploration setting. A first demonstration of autonomous navigation in a partially known environment has already been performed using the reactive autonomy software developed for the ROSA project [10].

Future work includes the installation of a LIDAR sensor on the mobile robot, the development of localization algorithms using interaction with an orbiter and the fusion of sensor information for guidance and navigation.

Figure 18: 2nd Generation rovers for network science

3.7 CART Experimental Testbed

The Canadian Space Agency's Automation and Robotics Testbed (CART) (Figure 19) is the main experimental robotic system at CSA. 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. Most of the technologies developed are being implemented on CART. For example, the Autonomous Robotics Ground Operation will be the main interface to CART. The SARAH hand and the ORPE stereovision system are being implemented for capture of payload using autonomous visual feedback control. A battery mockup has been developed to test some SPDM tasks.

Figure 19: CSA Automation and Robotics Testbed (CART)

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.

5 Reference

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