Proceeding of the 6th International Symposium on Artificial Intelligence and Robotics & Automation in Space:
i-SAIRAS 2001, Canadian Space Agency, St-Hubert, Quebec, Canada, June 18-22, 2001.

Validation of Ground Control Technology for International Space Station Robot Systems

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Keywords Ground-control, space robot, teleoperation, supervised autonomy, Mobile Servicing System, International Space Station, SSRMS, SPDM.

Abstract

The maintenance of the International Space Station, whether conducted by astronauts or robots, will require a lot of crew time. To remove some of this burden from the astronauts, it is proposed to conduct a portion of the robotic operations using the Mobile Servicing System from a ground station.

This paper describes an architecture to allow control of ISS robots from the ground. A concept of operation is proposed taking into account the current capabilities and limitations of the Mobile Servicing System (MSS). The system architecture is briefly described as well as the main sub-systems that make up the ground station. A strategy is presented to validate the proposed architecture using a set of representative mission scenarios and a high-fidelity simulator of the MSS.

1 Introduction

Canada's contribution to the International Space Station (ISS) is the Mobile Servicing System (MSS) [1], composed of the Mobile Remote Servicer Base System (MBS), the Space Station Remote Manipulator System (SSRMS) and the Special Purpose Dextrous Manipulator (SPDM). Figure 1 shows all three elements of the MSS mounted on the ISS truss.

The planned mode of operation for SSRMS and SPDM is teleoperation by an astronaut at the robotics work station inside the ISS. It is predicted that the operation of MSS will consume a lot of crew time because of the low velocities at which the SSRMS and SPDM will be operated and because of the potentially large displacements to be performed by these manipulators.

Figure 1: Mobile Servicing System

As an alternative to reduce the load imposed on astronauts by the operation of MSS, some of the MSS operations could be conducted from a ground station. SSRMS and SPDM provide control modes that would be suitable for ground operations and some of the hooks and scars necessary for ground control are already in the software. For example, it is already possible for ground-controllers to uplink data and configuration files to the MSS computers on-orbit.

However, ground control is hampered by communication link limitations such as time delays, bandwidth and drop-outs and by the lack of good situational awareness of the operator. To ensure that MSS operations could be safely carried-out from the ground, it is necessary to conduct a demonstration of ground control technologies in a realistic environment.

To perform this validation, CSA has developed a test-bed on which ground control technologies can be tested. The test-bed faithfully reproduces the interfaces, capabilities and dynamics of MSS as well as the communication limitations. The central component of the test-bed is the MSS Operation and Training Simulator (MOTS): a real-time simulator currently used for MSS operator training and for operation planning [2]. To simulate MSS ground control, an interface has been added to MOTS that will allow it to receive commands and transmit telemetry in the same fashion as the MSS will through the ISS command and telemetry servers. The first prototype implementation has been done using remote operation technologies that had been developed for a proof-of-concept demonstration [3].

To ensure that the technologies being developed meet operational needs, a review of the robotic missions that are already planned in detail for the space station assembly phases is being conducted. The salient features of each of these missions are being extracted and collated into a set of representative missions that will adequately represent the majority of foreseen uses of the ISS robotic systems. These generic missions are being used to create an operations concept document for ground operation of the MSS.

2 Concept of Operation

The existing operational environment imposes limitations on the selection of control modes for MSS ground operations. The presence of time delays, the limitations of bandwidth and, most importantly, the difficulty to set up continuous command streams to the ISS preclude direct teleoperation of MSS using the manual control modes. On the other hand, the lack of a complete suite of environment sensors and the limitations in computing power preclude fully autonomous operations. It is therefore proposed to use supervised autonomy to conduct MSS ground operations: the robots executing pre-generated scripts of motion commands under the supervision of an operator located on ground.

During execution, script elements are uploaded one at a time for execution. Safety-critical state transitions are controlled locally on-orbit by a safety and health monitoring system and do not require operator confirmation. This ensures that safety is not compromised by limitations of the communication link.

All logical branching decisions related to the execution of the script are controlled by a mission script executor, which is located in the ground station. The operator monitors the operation and is required to confirm every transition between script elements.

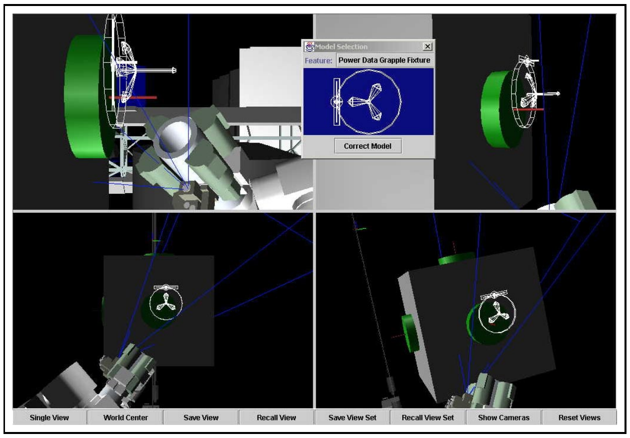
The on-orbit segment is then responsible for automatic execution of uplinked commands, relaying of telemetry and safety checking. To this end, an independent safety monitoring system is added to the already existing safety features monitoring MSS operations. This system monitors operations and has the capability to stop execution in case of unacceptable deviations from the nominal path or in case of imminent collisions. It is proposed to implement this feature using an on-orbit vision system tracking the posture of the arm and its proximity to ISS structural elements.

The ground segment is responsible for the generation and verification of the mission script, the execution of this script including uplinking of individual script elements, and the monitoring and control of transitions between script elements. A key feature of the ground segment is the ability to rehearse and modify the script on-line to remove the chance for human error and to account for discrepancies between the world model and the actual on-orbit environment based on sensor/visual data.

Mission scripts will generally be generated and thoroughly verified well in advance of their execution in space. During the planning phase, the generation and rehearsal is done using a nominal model of the environment, which might be slightly different from the real environment because of tolerances, thermal deformations or modelling inaccuracies. At execution, it will therefore be necessary to update the model based on sensor data and camera images being downlinked from ISS. Every script element will be verified before being uplinked to ensure that its success is not compromised by geometric modelling errors. If required, the script can be modified on-line and rehearsed using the updated environment model before being sent for execution.

For example, consider a script element that involves the approach by SSRMS of a Power Data Grapple Fixture (PDGF) for capture. Figure 2 shows a view of the ground operator station: the actual location of the PDGF is overlaid in wireframe on the world model. The script is first rehearsed without modifications to the world model to verify whether the PDGF will lie within the capture envelope of the SSRMS at the end of the script element. If necessary, the world model is corrected based on sensor data and the script is adjusted and rehearsed until it has been adequately verified. It is then uplinked to the MSS in preparation for execution.

During execution, the ground-based operator monitors the execution using telemetry and camera images. These are then used to verify the adequacy of the world model for the next step in the mission



Feature: Power Data Grapple Fixture

Figure 2: World Model Correction

script and the process is repeated until the completion of the mission.

In addition to relieving the crew from having to execute all robotic operations, this partitioning of the control functions between the ground segment and the flight segment has the additional advantage that the ground segment hardware and software are not subject to restrictions as severe as the flight segment. The computing resources available on the ground are virtually limitless and much easier to upgrade. It is therefore possible to provide much more powerful operator-assistance tools in the ground segment than will ever be possible on-orbit. Simple examples of such tools are virtual camera views from arbitrary viewpoints, visual and auditory cues, online path re-planning, automated task verification in the presence of anomalies, and automation of some of the more tedious tasks associated with the setting-up of the manipulator and loading of files.

3 System Architecture

The proposed ground control system architecture is based on the original on-orbit control architecture with minimal changes both to the system and to the method of operating it. Only the commands currently supported by the MSS are to be considered as script elements to be uplinked to the ISS.

The only modifications that are essential to conduct ground operations for MSS are modifications to the MSS flight software and the addition of an independent safety monitoring system.

The software changes are required to accept, from the ground, commands that are usually originating strictly from the Display and Control Panel or from the hand-controllers located at the Robotic Work Station on-board the ISS. The current implementation of the MSS control software requires a command originating from the D&CP or hand-controllers to trigger any motion of the arm.

Retaining the look and feel of the Robotic Work Station minimises the impact on the flight hardware and software and it preserves the relevance of skills necessary to perform ground based control. This allows trained astronauts to seamlessly transition from on-orbit control to ground-based control without requiring extensive re-training.

The original architecture for control of the MSS and the proposed architecture with added ground control capabilities are shown in Figures 3 and 4.

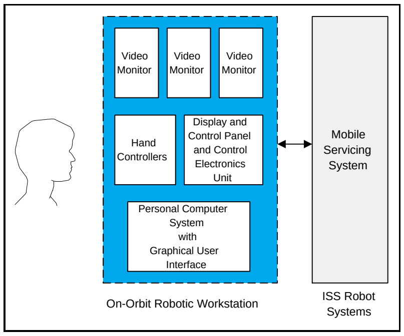


Figure 3: Command Architecture - On-Orbit Control

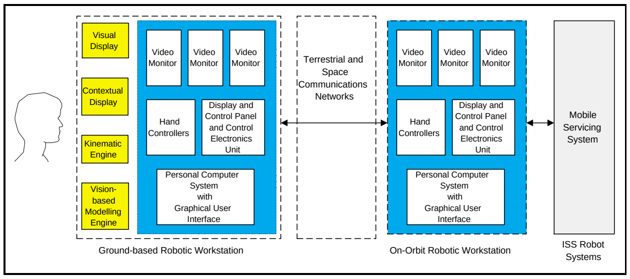


Figure 4: Command Architecture - Ground Control

As illustrated in the above figures, the modified system make minimal changes to the on-orbit portions of the system and replicates the on-orbit robotic workstation on the ground with four added functions. First a Visual Display is introduced to augment the operator's ability to perceive the on-orbit surroundings. Second, a Contextual Display is introduced to provide tools for constructing, editing and rehearsing mission scripts that will ultimately be used to directly control the system. Third, a kinematic engine is added to replace the calculations that are performed by the equipment controllers within the actual MSS on-orbit system. Finally, a Vision-based Modelling Engine is added to correct for critical dimensional errors that may have been introduced in the space station computer model.

3.1 Visual Display

The Visual Display provides the operator with a geometrically accurate representation of the MSS robots correctly posed and positioned within the space station surroundings. This display provides the operator with limitless virtual camera views generated by rendering and displaying a 3D computer model. The display can be configured to show a single full screen view or up to four simultaneous independent views (see Figure 5). These views can replicate the views of real cameras if desired, or they can provide views that could not be obtained from the on-orbit cameras. This display can thereby provide verification that the monitor views and the rendered model are consistent prior to planning or executing operations.

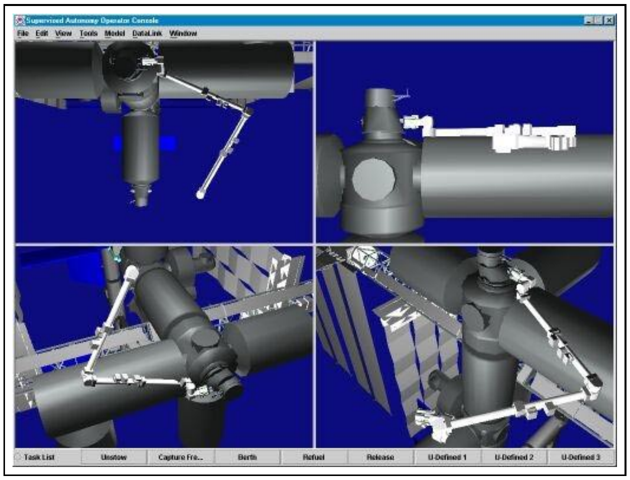


Figure 5: Visual Display on Ground Station

By observing the Visual Display and controlling the virtual MSS equipment models therein, the operator has a complete virtual environment within which to plan and rehearse operations prior to uploading any commands to on-orbit equipment. This environment also allows the operator to capture the motion of the virtual equipment models in script segment files. These script segments are transferred to the operator station's adjoining Contextual display where they may be interconnected to construct larger, more complex scripts. Scripts are ultimately uploaded to the on-orbit system and used to directly operate the MSS.

3.2 Contextual Display

The Contextual Display provides the operator with a graphical representation of each script segment, transferred from the Visual Display, as a single block that can be connected to other blocks to form a Mission Script that resembles a flow chart. Figure 6 illustrates the components of a Mission Script. Upon transfer from the Visual Display, each script segment block can be labelled with a name that is entered by the operator upon a query. For MSS operations, the operator will use the Contextual display to load, edit and rehearse mission scripts or script segments that have been transferred from the Visual Display.

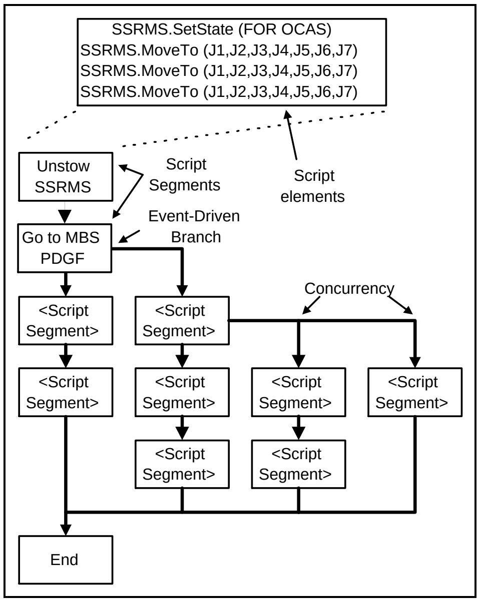


Figure 6: Typical Mission Script

The benefit of this approach is the removal of human error in the control of robot motion. All motion commands are stored and rehearsed in this manner, and only the acceptable motion command portions are retained for use in the actual operations of the on-orbit system. Unacceptable or erroneous motion command sequences are discarded and the corresponding script segment is regenerated, verified, and inserted into the correct location within the Mission Script

If desired, the operator can use additional tools provided in the Contextual Display to introduce logical branching conditions that are based on discrete sensory events. In a general sense this branching function preempts the currently executing segment(s) of a script in favour of an alternative segment(s) as determined by the sensed robot state or its interaction with the environment. This provides the capability for a robot system to respond to its environment autonomously by taking predictable, event-driven alternative courses of action. For MSS operations these branching conditions will be used to perform grapple fixture capture and release (an event-driven operation) and to implement safing in the event of anomalous operational occurrences, as contained in a detailed operations procedure.

3.3 Kinematic Engine

The Kinematic Engine performs the inverse kinematic and trajectory generation calculations necessary to operate the virtual MSS manipulator models with hand controllers, data entry or script rehearsal input. This function is performed by the robots themselves in the actual on-orbit systems and hence must be replicated in the ground-based operator station for the virtual robots.

3.4 Vision-based Modelling Engine

The Vision-based Modelling Engine performs local corrections on the space station 3D model using a combination of on-orbit camera images and manipulator telemetry data. The Vision-based Modelling Engine uses operator-selected camera images and model matching photogrammetry techniques to calculate the actual location and orientation of a known object such as a Power Data Grapple Fixture (PDGF) or a Micro Interface in relation to known camera locations. When commanded by the operator, the calculated corrected position is represented as a wireframe and the operator can then choose to accept or discard this correction. If accepted, the wireframe rendering is superimposed onto the model, as shown in Figure 2, wherein it may be used to manually or automatically correct the motion commands associated with the location of the object, such as grappling or other contact operations.

This would be used only during an active session where Mission Scripts are being uploaded and executed on-orbit and it is intended to correct for any minor dimensional errors due to model errors, manufacturing tolerances or thermally induced distortions.

4 Validation Scenarios

Representative missions of the MSS are used to validate the concept of ground control for MSS operations. These missions are selected such that they represent the majority of foreseen uses of the ISS robotic systems.

The first mission scenario simulates the deployment of the MBS using the SSRMS and its berthing to the Mobile Transporter (MT). This scenario contains many typical operations including powering up and down of the SSRMS, capture and release of a payload, free motion as well as constrained motion, and finally, powering of a payload through the tip Latching End-Effector (LEE). The second mission scenario being considered is a step-off and stow scenario. This procedure involves some of the same operations as the MBS deployment but, in addition, it requires a change of base of the SSRMS from one LEE to another. This type of operation is used to relocate the SSRMS all over the ISS: the SSRMS then walks end-over-end stepping on PDGFs located at different locations on the ISS.

These mission scenarios will be used to verify the feasibility of ground control for MSS operations. Tests will be conducted in nominal conditions and off-nominal conditions by inserting geometric modelling errors and malfunctions. The results of these simulations will be used to analyse the efficiency and safety of ground operations.

A demonstration of MSS ground operations will be performed during the conference using the proposed architecture and a high fidelity simulator of MSS operations: the MSS Operations and Training Simulator. Mission script planning, generation and rehearsal will take place locally at an operator ground station and the completed mission script data will be transmitted to the MOTS simulator via a communication link emulating the performance of the ISS communication infrastructure.

5 Conclusion

This paper describes an architecture to conduct a portion of the operations of robotic elements of the International Space Station from a ground station. This would free-up the most precious resource on space station: crew-time.

Taking into account the current capabilities and limitations of the MSS, it is proposed to conduct ground operations under supervised autonomy. An incremental implementation strategy is proposed to minimise the impact on flight hardware and software, and to minimise the amount of re-training to operate the system from the ground.

A validation of the system is conducted by running a set of representative mission scenarios on a test-bed whose central element is the MSS Operations and Training Simulator: the real-time simulator used for operator training and operations planning. The simulation runs are conducted under nominal and off-nominal conditions to assess the efficiency and safety of conducting ground operations.

At the moment, a thorough validation of MSS ground operations still has to be performed. After the concept has been tested and proven in a ground simulation, the next step in this research will be the development of a flight experiment on the ISS, conducting a portion of operations from a ground station in collaboration with an on-board operator. Such an experiment will be an incremental step from what was already done for the SSRMS' maiden mission. Indeed during this mission, all configuration files and commands were uploaded from the ground because of computer problems on-board the ISS. Only the final confirmation for every command and the control via the hand-controllers was done from on-orbit.

This research is also a stepping stone towards the development of autonomous space robotics applications such as reusable launch and space vehicles and planetary exploration. In many cases, these missions will be unmanned and the capability to control the robots from Earth will be required.

6 Acknowledgements

The authors wish to acknowledge the following individuals for their involvement in the work reflected in this paper: Eldon Wong, Joshua Richmond, Régent l'Archevêque, Mike Brousseau. Additionally, the authors express their sincere appreciation to the Canadian Space Agency and MD Robotics Limited for supporting this effort.

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