GROUND OPERATION OF ROBOTICS ON SPACE STATION FREEDOM

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ABSTRACT

This paper reflects work carried out on Ground Operated Telerobotics (GOT) in 1992 to refine further the ideas, procedures, and technologies needed to test the procedures in a high latency environment, and to integrate GOT into Space Station Freedom operations.

Space Station Freedom (SSF) will be in operation for 30 years, and will depend on robots to carry out a significant part of the assembly, maintenance and utilisation workload. Current plans call for on-orbit robotics to be operated by on-board crew members. This approach implies that on-orbit robotics operations use up considerable crew time, and that these operations cannot be carried out when SSF is un-manned.

GOT will allow robotic operations to be operated from the ground, with on-orbit crew interventions only when absolutely required.

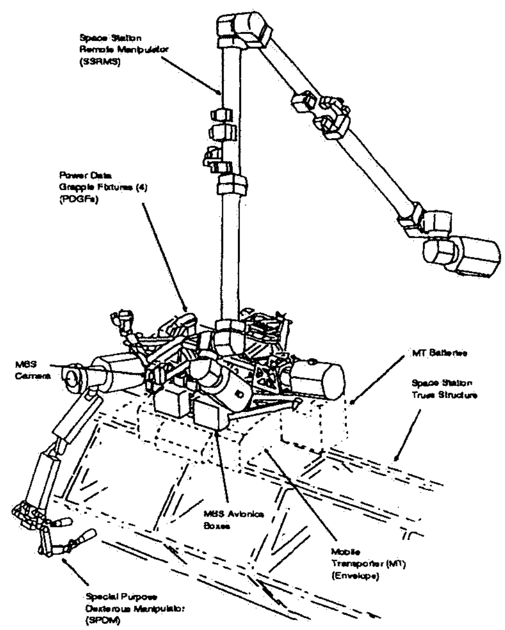
The paper reviews how GOT would be implemented, how GOT operations would be planned and supported, and reviews GOT issues, critical success factors and benefits.

1.0 GROUND OPERATION OF ROBOTICS ON SPACE STATION FREEDOM

The International Space Station Freedom is the largest international development project ever undertaken. Canada is a partner in SSF with the United States, Europe (European Space Agency, (ESA)) and Japan (National Space Development Agency of Japan, (NASDA)). The SSF will provide a permanent base in low earth orbit, for conducting space research in areas such as astronomy, life sciences and materials research.

SSF will be launched in late 1995, and will be in operation until the year 2030.

Canada's role within the SSF Program is to design, develop, implement and support operation of the Mobile Servicing System (MSS), an advanced on-orbit robotic system.



2.0 MSS ROLE AND OPERATION

The role of the MSS is to assist crew members in building, maintaining, utilising and in servicing SSF payloads, and to assist in the preparation for Extra Vehicular Activities (EVA) over the life of the SSF. During the SSF assembly phase, the maintenance workload is projected to be relatively high, possibly beyond the capacity of the resources currently planned to carry it out.

The current SSF Baseline Operation Plan calls for all robotic operations to be controlled by SSF crew. This approach implies that Extra Vehicular Robotics (EVR) will only be possible when SSF is manned, and when crew resources are available, ie. when EVR activities are in the plan. There will effectively be very little crew resource buffer available to meet any significant increase in the EVR workload, such as if the maintenance workload were to increase significantly beyond current projections.

3.0 GROUND OPERATED TELEROBOTICS

3.1 Description

Given a possible increase in the robotic workload, an approach to EVR where simple or repetitive robotics tasks could be executed without the use of crew members would appear desirable. Such an approach would imply ground-based operation of MSS robots, ie: Ground Operated Telerobotics. When fully implemented, GOT is the end-to-end execution of MSS tasks using ground-based personnel only. This paper will continue to refer to EVR as crew operated robotics, and GOT as ground operated operation of MSS.

3.2 Operational Concept

- Under full GOT, the MSS will be operated and controlled completely from the ground. Crew, when available, would only need to be involved in robotics operations when those operations interfered with other SSF activities, or when required to carry out specific difficult operations.

  GOT, as a relatively independent and unconstrained resource, would facilitate the Operations Planning of SSF, since GOT would usually be available for special tasks, workarounds, emergencies, etc.

- The GOT operator would use a stored procedure to command the MSS. This procedure would have been developed, verified and validated ahead of time by ground support personnel, and would include all steps required to execute the assigned task.

- The GOT operator would release commands step-by step, after having verified the successful completion of the previous step, simulated the next step and verified that the simulation results were consistent with the real environment on SSF.

- After releasing a given command, the GOT operator would watch the real MSS follow the simulated image, to ensure proper execution of that step.

- The GOT workstation would be on the ground, in the NASA Space Station Control Centre (SSCC) front-room, and would not use the "joy sticks" used on SSF.

- Should a malfunction occur, the GOT operator would intervene and/or pass the command of GOT over to crew members (i.e., back to normal EVR) if they are available on board SSF.

- GOT would not take place concurrently with unrelated EVA.

- GOT would be implemented in a carefully planned and integrated step-by-step fashion. A proposed stepped approach is discussed later in this paper. Each key step of GOT implementation would be verified and validated before the eventual inclusion of GOT into the SSF Program.

3.3 Impact on Robotics Support Team

The GOT Operator would be supported by the Robotics Support Team in exactly the same fashion as when a crew member is operating MSS.

The planned training and certification program for this staff would be upgraded, in order to support GOT, which is more flexible and dynamic than baselined EVR. The resulting job description and responsibilities would improve the job quality of the ground staff, and provide an enhanced career path for this staff.

3.4 Operations and Support Systems

GOT operation would use all Baseline EVR support systems. These would include the latest versions of:

- Path Planning. Collision Avoidance and Predictive Display Systems, using an SSF World Model when it becomes available.

- Artificial Vision Function (AVF). AVF would provide essential data to assist in capturing, aligning and berthing actions, by giving GOT operator essential information on position, attitude and movement of objects.

- Fail Safe Procedures and Alert System. GOT will require that these procedures be reviewed and upgradeable.

- Data and Video Telecommunication. It is estimated that GOT would not result in a significant increase in the Data/Video transmission requirement.

3.5 Space to Ground Latency

The major operational difference between EVR and GOT would be the latency of data and video signals. In EVR, the delay between the issuing of a command by the crew at the Control Station and the command starting its execution on MSS is virtually zero. In the case of GOT, the round-trip delay for command and data is of the order of 9 sec. Video images are delayed approximately four seconds from SSF to SSCC, and must be re-synchronised with the data.

Given this latency delay, the implementation of GOT will involve the development of specific Operations Plans and Procedures, and a stepped approach to that implementation. The safety aspect will also be addressed in the development of these procedures and in the implementation.

4.0 GOT IMPLEMENTATION PHASES

While GOT may not replace EVR for some operations, it is important to note that the Baseline Operations Plan (BOP) calls for the majority of robotic compatible tasks to be relatively simple. Based on this assumption, three areas of phasing have been defined: Control Level, Type of Activity and Point of Command.

4.1 Control Level

Control of SSF robotics would start with the baselined EVR approach, and would evolve through a gradual transfer of control to the ground operator (GOTO), using crew in a decreasingly active mode and an increasingly supervisory mode. During this phase, crew control could also be used for critical maneuvers, e.g., docking, latching, storage, etc., while simple actions such as translation would be carried out using GOT.

This evolution would culminate with full control of nominal SSF robotics by ground operators, ie. full GOT, with crew attention only in emergencies and when available.

4.2 Type of Robotic Activity

The nature of the activities to be carried out using GOT will evolve as skills, quality of procedures and knowledge grow. GOT will initially be used for simple translation of MSS, with or without cargo, including start-up, health status, return-to-base, safeing. Cargo may be any ORU, OMI or other on-orbit item. GOT would then evolve to contact (docking, grasp/de-grasp) and visual inspection tasks. The final step would be end-to-end control of a task, such as an ORU replacement.

4.3 Point of Command on the Ground

Another step in the implementation of GOT can be the actual location of the ground staff controlling GOT. Current GOT planning calls for the NASA Space Station Control Centre (SSCC) to be the ground command location. CSA will ensure that the implementation of the Canadian Engineering Support Centre (CESC) will not preclude the eventual control of GOT from the CESC, with the NASA Control Center in supervisory and support mode. Such a long-term evolution would only take place after GOT has been well tested and proven, with the full and active support of NASA Mission Operations Directorate (MOD) at JSC.

5.0 SPDM GROUND CONTROL STUDY AND TEST

In September of 1992, the Robotics Systems Evaluation Laboratory, located at the Lyndon B. Johnson Space Center in Houston, Texas, conducted a Special Purpose Dexterous Manipulator (SPDM) Ground Control Study. This study was conducted to evaluate the feasibility and impact of implementing ground control for robotic operations on Space Station Freedom.

This test attempted to answer some of these questions, by performing a representative robotic task using four different modes of operation: teleoperation without and with ground based time delay, teleoperation with ground based time delay and a predictive display, and a semi-autonomous/supervisory mode with ground based time delay. Teleoperation without time delay effectively replicates EVR, and provides a basis for comparison between manual EVR operation of MSS and manual operation of the robot from the ground, with the time delay.

The usefulness of predictive displays was evaluated by comparing the second and third control modes.

The study also compared the performance of teleoperation with semi-autonomous modes for robotic ground control. In this study, semi-autonomous mode refers to the use of a combination of teleoperation and autosequence commands to perform the task.

The complete SPDM Ground Control Study will eventually be made up of several test phases. The first phase of testing involved performing a combined inspection and EVA worksite setup task, and an ORU acquisition and stowage, using a telemetry roundtrip delay of 9 seconds and a command/video roundtrip delay of 6 seconds.

Preliminary results have shown that the combined use of a predictive display system and stored procedures reduces both the number of errors from the operators and the elapsed time required to perform the tasks. The resulting elapsed time is of the same order of magnitude as basic teleoperation, without time delays, ie. normal EVR.

6.0 GOT IMPLEMENTATION: OTHER ISSUES

6.1 MSS Command Hardware and Software

In order to execute MSS commands issued from the ground, the SSF Control software must be modified, as the current design requires that the MSS operator "arm" the system by physically depressing a switch on one of the joysticks, before "firing" a stored command or moving the stick.

6.2 Impact on SSF

It is likely that using GOT will increase the actual usage of MSS robots, and increase propellant and power consumption aboard the MSS. The resulting wear-and-tear on all components must be monitored, with maintenance and evolution of the design being followed up carefully. Spares, logistics, re-supply and robotic compatibility of spares are further design and planning issues which must be addressed.

6.3 Verification of GOT

Each GOT implementation step must be verified and validated (V&V) by ground personnel and by crew. This V&V process must be built into the MSS Mission plans, as soon as enough MSS hardware and software are available to begin executing GOT, i.e. MB-7. Another possible method of validation would be by emulating GOT using the SS Orbiter and its robotic arm, the SRMS.

7.0 BENEFITS OF GOT

GOT benefits have been identified and quantified to varying degrees in several papers and documents.

7.1 Time-Delayed Remote Operation and Maintenance of Space Station Freedom

This IAF 1991 paper analyzes a particular MSS ORU replacement operation, similar to the SPDM Ground Control Study and Test discussed elsewhere in this paper. The conclusions of this paper were consistent with the SPDM study, even though this paper was of a more theoretical nature, and was used as a starting point for the GOT concept.

7.2 SPDM Robot/Astronaut Comparison with Respect to SSF Operation

This IAF 1991 paper compared end-to-end elapsed time, (i.e., crew task time) to change a given ORU using robotics in one case and Extra Vehicular Activity (EVA) in the other.

The conclusions of this paper were also consistent with the SPDM study, in addition to highliting the reduction in crew attention which can be achieved by using GOT.

7.3 Other benefits of GOT

GOT in itself is a virtually limitless resource, bounded only by the reliability of the MSS, and the availability of SSF resources and MSS spares. In addition to providing direct savings in IVA and EVA time, GOT will benefit the SSF program in several other ways:

- Availability of Robotics. In the short and the long term, GOT would allow space robotics to become an unlimited resource, capable of executing not only maintenance tasks (corrective, preventive) but also janitorial tasks, inspections, calibration of equipment and the execution of some space experiments or other dangerous tasks.
- Greater Effectiveness and Availability of SSF. Using GOT to reduce the maintenance backlog will result in an improved and more efficient SSF, and would reduce the impact on SSF of an accumulation of individually non-critical ORU/OMI failures. Should the pre-MTC Mission Build flight schedule slip and leave SSF unmanned for even longer periods, GOT will continue to ensure Maintenance Actions are carried out.
- Greater Flexibility in Short Term Planning. Using GOT to address urgent or time consuming tasks, without crew availability restrictions, would give mission planners more freedom to plan for productive work for the crew, and more freedom to react to emergencies during both manned and un-manned periods.
- GOT Expert Systems. Over time, GOT would allow the construction of a knowledge base from which better Procedures, Mission Planning and Execution Tools can be developed. Such databases and associated Expert Systems will not only improve the operation of SSF but will also have direct commercial applications.
- Enhanced Role of Ground Staff. Implementation of GOT would increase the importance and influence of Robotics related ground positions. This would be beneficial in terms of morale, career path and personal development, and result in an increased role for trainers and related ground installations.
- Cost Effectiveness. In all the above cases, GOT would also reduce the cost of the overall program, since ground personnel and equipment is almost certainly cheaper to build and use, and more flexible

than on-orbit personnel and equipment.

- GOT in the Commercial World. The development and implementation of GOT has direct commercial applicability. Space represents extremes in distance, latency, hostility of environment and complexity.

8.0 RISK ASSESSMENT

On-Orbit safety is of vital importance. GOT calls for the implementation of new techniques and procedures, all of which have a direct impact on the day-to-day operation of SSF. Since GOT involves the movement of important masses, this movement will imply a constantly changing "World" in SSF, and since GOT will release crew resources to carry out other activities, it is critical that all GOT related Principles of Operation, Procedures, and actual operations be thoroughly developed, documented, tested, validated, approved and integrated into the SSF operations plan.

R&D requirements are well in hand, since GOT requires no extra techniques or support systems above and beyond those already planned for SSF.

From the programmatic point of view, GOT must be fully integrated into the document flow, starting at the Operations Concept and Plans level, and flowing down to requirements, specifications, design and implementation.

9.0 CRITICAL SUCCESS FACTORS

To be successfully implemented and used, GOT needs the following factors to be addressed.

Implementation of GOT will require funding over and above current SSF program budgets. It is also vital that SSF and MSS not be re-scoped in such a way as to preclude the implementation of GOT. Further, for GOT to be successfully integrated into SSF operations, the concept must be fully supported by all NASA contractors and partners.

Finally, several elements of MSS, both on-orbit and on the ground, will need to be modified or improved in order to implement GOT.

- MSS hardware will need to be monitored closely to ensure that the increased work load does not negatively impact the ability of MSS to execute mission critical tasks. The resulting spares and logistics issues must also be addressed.

- MSS software will need to be modified to allow for the execution of MSS commands which are issued from the ground.

- Management, support and staffing on the ground must allow for real-time support of GOT and for the development and validation of MSS procedures in real-time, without the involvement of on-orbit crew.

- All robotics activity on SSF, both in EVR and in GOT modes, will depend entirely on video cameras, lighting and a sophisticated Advanced Vision Facility (AVF), thereby further increasing the importance of that aspect of robotics operations on SSF.

- The SSF/MSS high fidelity simulator used in the MSS Procedure development process and during GOT execution of these procedures must be capable of operating in real-time mode, be easily updated to reflect the actual SSF "world" at any given time, and must be available to execute nominal procedures as GOT is in execution, while real-time simulating an amended procedure as the procedure in execution is being revised.

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