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Space Automation and Robotics activities past, present and future: next steps for a robotics laboratory

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ABSTRACT
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SPACE AUTOMATION AND ROBOTICS ACTIVITIES PAST, PRESENT AND FUTURE: NEXT STEPS FOR A ROBOTICS LABORATORY

by

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ABSTRACT

An Automation and Robotics (A&R) laboratory is being developed at the National Aerospace Laboratory NLR. The laboratory is intended to be a testbed for harmonized ESA/Dutch operations technology. A number of activities related to (internal) A&R are reviewed. A reference scenario involving liquid sloshing experiments based on an external robot arm is analysed to suggest next steps for further developments. Remote utilization of robotics technology is emphasised.

1. INTRODUCTION

To contribute in the developments needed for utilization of the space segment, the National Aerospace Laboratory NLR participated in a number of simulation activities relevant to robotics. The HERA Simulation Facility Pilot was developed (Ref. 1) for external robotics. Payload automation and internal robotics interaction was studied in the ARCADE project (Ref. 2). In parallel telescience, teleoperation and crew support has been studied (Refs. 3,4). Flight experience has been obtained with the Two-Phase-eXperiment (TPX), with the Wet Satellite Model (WSM) experiments in preparing for Sloshsat FLEVO (Ref. 5) and with remote operations for the Critical Point Facility (CPF).

In chapter 2 activities are evaluated from the point of view of internal robotics. A case study based on fluid dynamics experiments executed by an external robot is the basis for exploring opportunities in utilizing state of the art external robotics methodology (chapter 3). The case study illustrates next steps needed to improve infrastructure for future automation and robotics utilization (chapter 4).

2. INTERNAL ROBOTICS

In the following a number of projects are discussed in order to extract lessons learned for internal robotics.

General measurement requirements for fluid physics experiment facilities as identified in a µ-gravity instrumentation study for a future space laboratory, motivated the early development of the Prototype Optical Diagnostic Instrument (PODI). The breadboard was extended to TelePODI to allow for telescience studies. Remote control of diagnostics was studied in teleoperated mode such as: a scene observation system, a Twyman-Green interferometer and a Schlieren system. Supervisory control concepts as being developed for telerobotics (interactive autonomy) proved to be useful. This was demonstrated for optics control in the presence of delays involving some on-board autonomy.

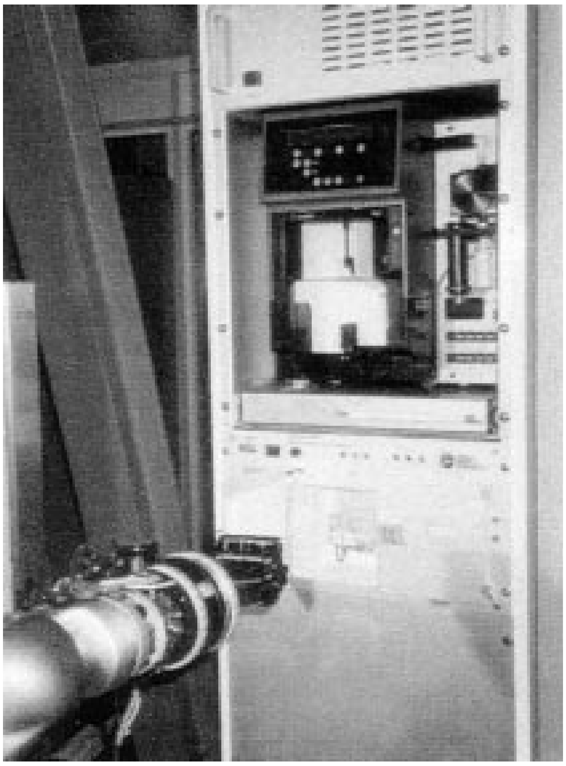

Fig.1 ARCADE setup

The application of robotics in TelePODI was analyzed using graphics based simulations (using the ROBCAD software package). Considerations related to limited uploads and frequency of exchanges make a robot arm external to the facility difficult to motivate. For example, experiment cell containers were too big (10 - 15 kg) and automated exchange of 1 liter liquid cells (as in PODI) was considered impossible by experiment container designers. Furthermore, only a few containers were expected to be available during a campaign of many months, which makes it difficult to motivate a robot or internal automation for container exchange when crew is around.

Commercially available High Performance Capillary Electrophoresis (HPCE) equipment in combination with an engineering model of the Glovebox are available to study crew interaction (DUC/DAMS project, Ref. 3).
For the study of internal robotics, a similar HPCE payload is available (ARCADE, Ref. 2 and Fig. 1) which bas been integrated in the Columbus Automation Testbed (CAT). Using graphical simulations (using the ROBCAD package) a complete redesign of an HPCE system with respect to payload internal A&R has been considered. However, it was considered too costly to realize a dedicated design for automation. A compromise was selected in which test samples where moved between an incubator and a commercially available, but rebuilt HPCE. Simulations showed that crew could be eliminated for a major part of HPCE analysis. However, as crew is involved in sample preparation, the gain in valuable crew time when using robotics could not be fully demonstrated. Modifications of the experiments are being considered to make better comparisons.

The above shows that frequency of robotics operations and (re)design costs can be considered a major bottleneck for internal robotics application in the near future. The choice of experiment is also very important. For experiments involving a high frequency of operations, A&R will evolve more naturally. For example, a miniature microscopy set-up with small samples would allow a high frequency of experiment cell exchange. In conclusion a prerequisite for improving applications will be optimization for robotics application at the conception of experiments. This will allow avoiding redesign costs and will improve robotics application.

3. ROBOT SLOSH EXPERIMENT CASE STUDY

3.1 External robotics

The frequency of external robot operations can be much higher than the frequencies possible for extravehicular crew activities. Therefore, from a user point of view the design for use with an external robot is more attractive. As will be shown in the following a fluid-dynamics sloshing experiment can be used for analysis of future external robot applications.

The European Robotics Arm (ERA) is being developed to transport large structures and its development will increase robotics experience. In parallel technology is being developed for smaller arms. Precursor developments can be based on JERICO and the Spider manipulator, which will be integrated on the MIR station (Ref. 6). To prepare for future space station utilization new experiments are being solicited related to the JERICO developments (Ref. 7).

The CAT testbed at ESTEC has been extended with a functional model of an external payload platform anticipating a future need for simulations. This NLR development will be available for breadboard test preparations and allow accommodation of models for a Materials Exposure Facility (MEF) and/or EXPRESS pallet adapters.

When an external robot is available for handling of a tank partially filled with liquid, the sensor package and the actuator system of the robot can replace measurement and excitation systems needed for performing sloshing experiments, in theory. This motivates a more detailed study. In the following the experiment is introduced and open items are addressed. The case analysis will show elements required to improve A&R technology.

3.2 Background fluid-dynamics experiment

The ability to understand, predict, and accurately control the dynamics of spacecraft with large amounts of liquid on-board becomes more and more important. Pointing and stability requirements increase relatively fast, for both scientific and telecommunication satellites. To contribute to the solution of this problem, the National Aerospace Laboratory NLR has conducted several "micro-gravity" fluid/spacecraft dynamics interaction experiments, such as aircraft parabolic flight experiments, a Spacelab 1 and D1 based experiment and a sounding rocket experiment.

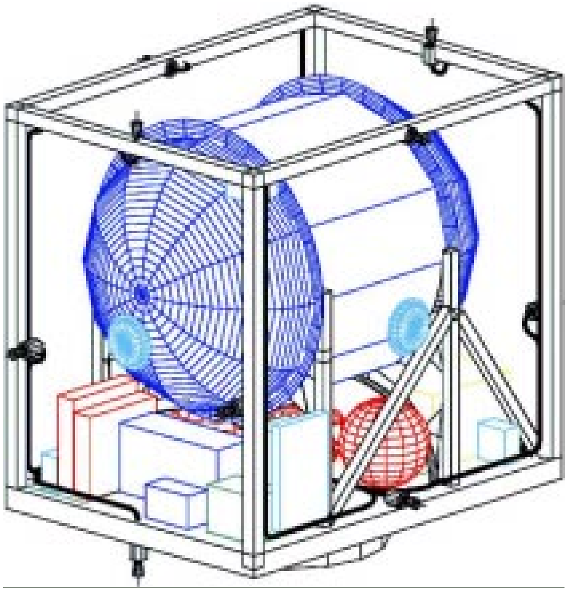

Fig. 2. Overview of Sloshsat FLEVO

The need for a more advanced flight experiment was voiced, with a much longer experiment duration, a 3-D tank, a choice of 3-D excitation possibilities, much more elaborate tank instrumentation and multiple experiment runs controllable by the experimenters, etc. As a result Sloshsat FLEVO has been defined.

The payload of the satellite consists of an experiment tank with elaborate instrumentation (Fig. 2). The tank shape is a circular cylinder with hemispherical ends and no internal structures. The volume of the tank is 87 liters. The tank will be partially filled with 33.5 liters of water. With a sensor system, the liquid height at the tank wall will be measured at 270 locations. Additional sensors are provided at a few locations to measure liquid height with a better resolution, liquid velocity at the wall, pressures and temperatures. The mass of the dry satellite is approximately 90 kg. The fluid/rigid mass ratio is about 0.4. The satellite will be launched from a Shuttle/Hitchhiker. The free-flying mini-satellite will be designed for a total of at least 24 hours of fluid/spacecraft interaction experiments, executed in several experiment blocks during the duration of the Shuttle flight of approximately 2 weeks.

3.3 Approach using robotics

During Spacelab-1 and D1 mission small containers filled with liquid were available for the Fluid Physics Module to study sloshing (Ref. 8). Execution of the experiments using an internal robot arm has been studied (Ref. 9) previously. Due to uncertainties in future availability of an internal robot arm this option was not pursued.

A robotics manipulator for performing experiments with a tank filled with liquid, will offer the following benefits in realizing scientific return:

- A manipulator is an accurate and repeatable means of liquid tank excitation, contributing more than 'just' operational/servicing resources.
- The advanced sensor and drives package of the robot arm will act as closed loop force-torque sensor and actuators.

In addition, the experiment might fill utilization gaps in the manipulator time line.

Previous telescience experiences suggest the following when trying to improve utilization for a robot:

- Design for repeatable or reversible experiments.
  A closed experiment tank filled with liquid meets this requirement.
- Early involvement/interest of a large user community.
  Liquid dynamics experiments are interesting from a science point of view and have substantial technological interest for the development of future payloads.
- Ensure continuity in a research program.
  SloshSat FLEVO will only be available for a few weeks for experiments. With a robot as in JERICO a long term research program will, in principle, be possible.
- Allow remote operations.
  During the design, testing, training, execution and post-processing remote operations will contribute in cost-effective "plug-and-play" solutions (Ref. 4) and active user involvement.
- Integrate quantitative simulation tools.
  Various simulators are available related to sloshing experiments. More specifically a SloshSat Motion Simulation (SMS) package has been developed (Ref. 10).
- Integrate autonomous scenarios.
  When autonomous scenarios (possibly sub-optimal) are possible, link-outages will not be critical for the utilization. Autonomous experiment execution has been demonstrated in a Wet Satellite Model experiment.

Preliminary indications are that a number of tank configurations complementary to SloshSat can be considered:

- A tank cavity with two cylinders to allow reduction to 2-D treatment of liquid flow (WSM)
- Experiments involving controlled rotations.
- Experiments involving controlled acceleration.

Moreover, previously a set of liquid cells has been proposed (Ref. 8) and currently a number of experiment proposals are being developed by an international Investigators Working Group (IWG) which controls the design and execution of the SlohSat experiments.

Verification of algorithms to identify interface forces, as also occur between liquid and tank, is of considerable current interest (Ref. 11). In a non-roating spherical tank, liquid torque can be neglected. However in a non-spherical tank the measured liquid torque (in addition to liquid force) will be a precise diagnostic tool for the evaluation of the flowfield. The tank should be partially filled only, for µ-g relevance. Rotating tanks bring additional opportunities for force/torque identification, in relation to tank shape and fill fraction.

3.4 Issues in experiment redesign

When trying to develop a sloshing experiment version for an external platform many problems need to be solved.

The thermal design is considered solvable, but clearly precautions are needed to avoid freezing and boiling. The thermal gradients inside a container over an orbit need to be evaluated with respect to the scientific objectives. Detailed analysis may even result in proposals for new thermo-fluid dynamics experiments.

In the vicinity of the space station safety regulations are an important cost-factor for redesign. This will include safety aspects during grappling and manipulation, µ-g disturbances and fracture analysis.

To make maximal use of the external robot a trade-off is needed between having several small tanks (e.g. similar to Spacelab proposals) and using one big tank. Specifically, the sensitivity of the force/torque transducer should be taken into account in a trade-off. The weight of a stripped version of Sloshsat will approach the design limits for JERICO. To avoid corresponding risks and upload costs, small experiments have advantages. To have a pallet of small experiments is clearly more attractive from a scientific point of view. Such an approach would allow many scientists and students to perform experiments repeatedly over a long period.

To minimize the design costs, the sensor package of the robot can replace experiment sensors. However, when during the scientific analysis it is concluded that the sensor data package of the robot is not sufficient, additional measurement systems may need to be (re-)designed. The existing ballistometer will be a good starting point when needed. The measurement systems can be powered by solar cells or via the robot. Not only power supplies but also a need for the development of a (contactless) data exchange interface may become apparent.

The design of the tank might be adjusted to the robot capabilities. For example, from a torque point of view, the handling of a sphere will be easier than handling of a cylinder. The required motions for the experiment need to be matched with the capabilities of the robot controller and may involve experiment redesign. For example, prolonged rotation will not be feasible unless provided for in the test container. Limitations in programming of acceleration profiles are to be expected. Even complex tracking operations can be envisaged.

Cameras will be available for external robot systems. These cameras are proposed for calibration of the robot sensor systems. Visualization of sloshing experiments is more difficult as the robot cameras will be optimized for operation taking into account illumination of the sun. An experiment observation via a looking glass will require additional illumination to look inside a container. Special viewing aids may need development or mirror set-ups to visualise three-dimensional phenomena with one camera. Increasingly, autonomous image processing is becoming feasible for more complex tasks (including calibration of the robot system) as is being demonstrated in various robot vision projects (CALVIN and VALVIS study). Human-assisted robot vision is feasible but realism of simulations needs to be enhanced before space application can be considered. Of particular concern are video resolution requirements. Using precursor experiments to WSM a number of feasibility analysis have been performed previously related to autonomous image processing. In a small study performed by the Dutch company Geodelta, it was confirmed that photogrammetric techniques using photo's are superior to robot vision based on standard video cameras.

Clearly, redesign costs will be involved. However, the redesign costs should be relatively low in comparison with the redesign of a complete instrument.

4. NEXT STEPS

4.1 Operational experience in simulations

A number of suggestions for next steps in developing robot technology can be drawn from the robot sloshing experiment concept.

Increasing operational experience using ground simulation set-ups is an obvious starting point for further developments. The existing simulation facilities at ESTEC and NLR can be modified to gain necessary experience. Although space A&R is widely recognized as a promising and even critical technology, it has not yet reached the maturity and user-acceptance of earthbound counterparts. Operational experience will contribute in acceptance. However, the previous sections suggest that more will be needed.

4.2 Robotics improvements

For the robot arm the following may be considered in next steps:

- Non-cooperative object simulation.
  A container filled with liquid will pose special requirements for handling by a robot arm and can be considered to have many elements of non cooperative objects. Set-ups involving gyros may ensure reproducable results in simulating various handling scenarios.
- Calibration
  Calibration equipment is needed to analyze robot sensor equipment.
- Enhanced realism of robotics control.
  Improvements in testbed environments for robotics can be motivated in a better way when the interfaces involved can be reused for the flight developments.
- Robot interface development
  For active objects interfaces (possibly contactless) will need to be developed.

4.3 Environmental modelling

Typically, the following environmental modelling needs to be considered for a next generation of robotics testbeds to be able to handle a "sloshing experiment", next to modelling of μ-g:

- Link-budget simulation.
  To allow for realistic simulations software will be required to simulate link-budgets during operations.
- Thermal simulation.
  Integration with orbital simulation is needed to identify and test constraints on the external payload operations.
- Simulation of illumination conditions
  Moreover, simulation of illumination conditions is needed to take into account the sun and the implications on camera design. This became apparent during analysis of the ERA Camera and Lighting Unit.
- Computing resources simulation.

Of special interest would be to have representative processing modules available for space qualified experiment design.

4.4 Remote user workstation and datanetworking

Other improvements which need to be considered are:

- Visual observation correction
  In future, various types of real-time image processing will be available to present the remote site with optimal information. This can include real-time warping to allow for special lenses.
- User interfacing
  "Plug-and-play" user interfaces which are platform independent are being demonstrated in ground simulation set-ups and should be pursued for the flight segment.
- Interactive payload control
  Of special interest would be payload control methodology which allows to improve robustness when performing experiments remotely. The interactive autonomy concept is very relevant. However, it is recommended to offer a broad range of teleoperation options. Sufficient operational experience using ground set-ups as improved teleoperation is expected to improve utilization considerably.

In existing robotics testbeds communication protocols have little overlap with the real space infrastructure. This should be improved following two approaches:

- Application of commercially available standards in testbeds for the space segment whenever possible.
- Upgrading of existing space standards (CCSDS) implementations.

Following experiences with ISDN and internet (Ref. 4), comparison with ATM (Asynchronous Transfer Mode) has been explored for telerobotics. Both an ISDN and ATM based multimedia link could be established between the Delft University of Technology and NLR (Fig. 3).

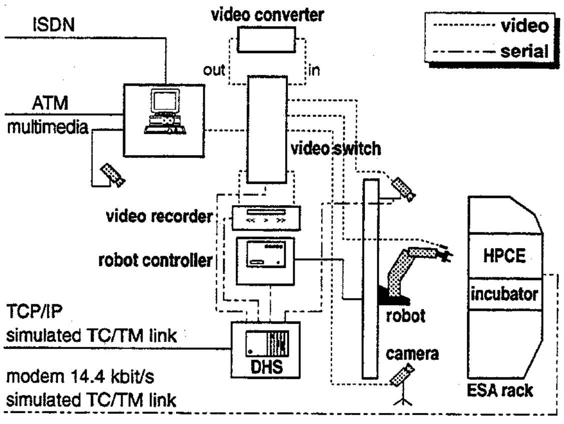

Fig. 3 Telerobotics with remote visualization via ISDN and/or ATM

As part of the Advanced Communication Technologies and Services (ACTS) in the Fourth Framework program of the European Union (EU), experience is being extended with telerobotics using an international ATM network pilot. Although a cost-benefit analysis is not yet possible, experiences suggest that technology for cooperative engineering will continue to increase dramatically for the ground segment.

5. CONCLUSIONS

The following is concluded with respect to next steps required for the further development of A&R technology (which will partly be realized in NLR facilities):

- Continue to use existing A&R facilities and payloads for internal robotics to develop new applications. Of particular interest would be the development of miniature payloads suited for A&R (chapter 2).
- Perform a number of "design for robotics" studies in sufficient detail to allow well-founded marketing of robotics applications. A Sloshing experiment is considered to be a good candidate for such a study (chapter 3) and in addition contribute real value.
- Upgrade or redesign simulation facilities in such a way that incremental integration in flight experiments is possible which includes consistent interfaces for ground and space segment. Use remote access to payload control to promote a robotics approach for a large community using low-cost teleoperation scenarios (chapter 4).

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