

SYSTEM PREREQUISITES AND OPERATIONAL MODES FOR ON ORBIT SERVICING

ISTS (International Symposium on Space Technology and Science)

Miyazaki, Japan, May 30 – June 6, 2004

K. Landzettel, B. Brunner, R. Lampariello, C. Preusche, D. Reintsema, G. Hirzinger

DLR German Aerospace Center, Institute of Robotics and Mechatronics

D-82230 Oberpfaffenhofen

(E-mail : klaus.landzettel@dlr.de)

Abstract

The increasing number of launched satellites per year calls for solutions to keep free operational space for telecommunication systems in GEO, as well as to avoid the endangering of space systems in LEO and of the public living on Earth. Malfunctions of satellite sub-systems like solar generators, control systems, or thrusters cannot be avoided. Therefore, on-orbit servicing (OOS) will be a mandatory and challenging topic for space robotics in the near future. The outcome of national German projects like ROTEX, ESS and GETEX/ETS-VII represent a know-how which can be directly applied for the development of OOS robotics systems. The recently started national project ROKVISS already provides the necessary space-qualified hardware as well as the very powerful tele-presence operational mode. The space robotics mission TECSAS (Technology Satellite for Demonstration and Verification of Space Systems), is a very good opportunity to demonstrate and verify satellite capturing strategies.

The first business case for on-orbit servicing will hopefully become reality within the next few years. Orbital Recovery Ltd. has initiated its Spacecraft Life Extension System (SLES™). SLES will operate as an orbital tugboat, supplying the propulsion, navigation and guidance to keep a telecommunications satellite in its dedicated orbital slot for several additional years.

1 Introduction

Upcoming space robotics systems are planned as free-flying orbital servicing vehicles for maintenance, repair, station keeping, or de-orbiting of failed satellites. These systems will be controlled in telemanipulation and/or tele-presence mode. But all these proposed new systems are still in the preparation phase. A lot of know-how concerning the operation of space robots was gained during previous space robotics missions, but still there exist few technology gaps which have to be closed

within the next years in order to apply robot technologies for sophisticated OOS. Telecommunication systems which fulfill the tele-presence requirements and allow telemanipulation in LEO via relay satellites in GEO for approx. 20 minutes (and more) are indispensable. Furthermore sensor-controlled light-weight, mechatronic arms as well as articulated, multi-fingered hands in conjunction with powerful tele-operation systems, allowing the operation of robots on free-flying platforms are mandatory for future OOS systems.

2 Previous Work

ROTEX, the first remotely controlled robot in space [1] flew with Spacelab-Mission D2 in 1993 and performed several prototypic tasks like assembling a truss structure or catching a free-floating object in different operational modes, e.g. off-line programmed, but also tele-operated from ground by man and machine intelligence. The experiment prepared different prototypic applications for assembly and external servicing. The most relevant experiment for OOS was the autonomous catching of a free-floating object. This experiment may be considered as a precursor mission to the long-term goal of capturing a non-cooperative, tumbling satellite in free space. Due to the lack of space proven image processing hardware for the capturing experiment, the control loop was closed via an image processing system on ground. The varying total signal round trip time was continuously determined during experiment execution and regarded for the prediction of the free floating part's position [2]. This principle may be directly applied to today's satellite repair missions in order to keep the required hardware effort for the spacecraft as low as possible.

ESS, a national financed study, was dedicated to investigate in detail the dynamical behavior of a free-flying servicing satellite [5]. The focus was on the influence of the robot arm motion to the pose (position & orientation) of the chaser satellite. A HIL (hardware in the loop) simulator (Fig. 1) was developed allowing the simulation

of the mission critical final approach and capturing phases.

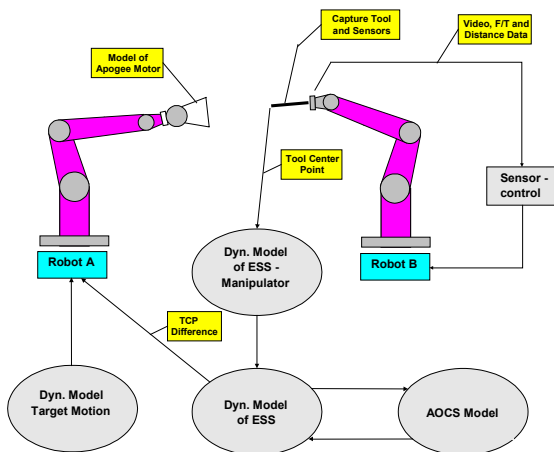


Fig. 1 ESS HIL-Simulator

A capture tool, containing 6 laser range finders, a wrist-mounted force-torque sensor, and a stereo camera pair was developed at DLR, allowing the capturing of a satellite at its kick-motor's nozzle, which is typical for most satellites in GEO. A space qualified version of this capture tool, as well as the shared control strategies will be applied for the SLES.

GETEX, was a big chance for DLR to participate in the Japanese ETS-VII project, the first free-flying space robot, and to verify the ESS study results. In April 1999 we got the permission by NASDA to remotely program and control the ETS-VII robot from our ground station, located in Tsukuba/Japan. The main goal of DLR's contribution within GETEX [3]&[4] was to verify the dynamic models of the interaction between a robot arm and its free-flying carrier. The results, gained from this experiment, represent an important step towards a real free-flying service satellite. The free-floating mode of operation is of interest for space robots not only for the reason that attitude control fuel may be saved, it will also be of importance during repair missions, when the servicing satellite is very close or in contact to the target satellite: any action of the attitude control system of either of the two satellites during this phase could lead to a collision and thus to a potential damage on the two spacecrafts. Whatever path planning method is applied to free-floating robots, it will be necessarily highly model-based. The parameters of the dynamic model have therefore to be known quite well. While this poses no problem for the geometric parameters and for the mass and inertia of the manipulator, the mass and the inertia of the spacecraft are subject to important changes during the lifetime of a servicing satellite. Therefore, the identifica-

tion of the mass properties of the ETS-VII satellite, after more than one year of activity in orbit, was an important result of this experiment, too.

MARCO (Modular Automation and Robotics Controller), based on the know-how gained from ROTEX, provides direct telemanipulation as well as off-line programming combined with features for autonomous execution. The development goal for this high-level programming system was to design a unified concept for a flexible, highly interactive, on-line programmable tele-operation station as well as an off-line programming tool, including all the powerful sensor-based control features, as tested already in ROTEX. In addition, MARCO provides the possibility to program a robot system at an implicit, task-directed level. On the User or Payload Expert layer (Fig. 2) the instruction set is reduced to what has to be done, no specific robot actions will be considered at this task-oriented level. On the other hand the robot system has to know how the task can be successfully executed, which is described in the explicit Robotic Expert control layers.

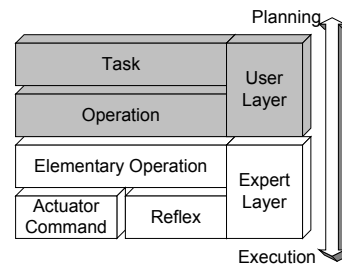


Fig. 2 MARCO Control Layers

3 Robotics Technologies required for OOS

When comparing human skills with those of present-day robots, of course human beings in general are by far superior, but when comparing the skill of an astronaut in a clumsy space-suit with that of the best available robot technology, then the differences are becoming smaller. For IVA activities e.g. a robot basically would have to compare with the full human skill and mobility. To be honest, many of the manual operations to be done in a space-laboratory environment are fairly simple standard operations, like handling parts, opening and closing doors, pulling drawers, pushing buttons etc. which have to be done just by stepping through extensive, written procedures. Real intuition and manual skill is particularly requested in non-nominal situations. It is obvious that even with today's technology and the available tele-robotic concepts based on close co-operation between man and machine, there are many tasks in space, where robots can

replace or at least augment human activities with reduced cost from a mid-term perspective.

Space robotic applications demand light weight arms for safety and cost reasons, human friendly interaction, as well as a certain degree mobility. A load to weight ratio of 1:1 similar to that of the human arm is desired. Interaction with unknown environments needs compliant arms and fingers, facilitated by the information of many different sensors and advanced control strategies. To integrate different multisensory components as arms, hands, and maybe mobile platforms, sophisticated mechatronic concepts and an adequate, flexible architecture of the control system are needed. DLR's new robot arm concept aimed at a completely modular assembly system with only a few basic components concerning joint mechanics, electronics and links.

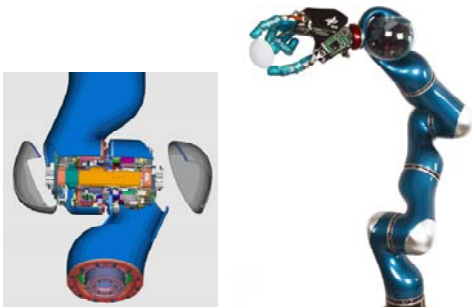


Fig. 3 DLR's light Weight Robot Arm

In general the modular concept gives a number of advantages, e.g. rotation symmetric components, few single parts, short force transmission from bearing to off-drive connection, identical design for pitch and roll joints, big hollow shaft in all joints with up to 30 mm diameter, enabling the placement of cable and plug links inside the arm.

In addition to the mechanical modularity, also the robot electronics is designed in a modular manner. Each joint unit contains the power electronics for the motor and a motor current controller board, analog and digital signal processing hardware for the sensor signals and a DSP board for decentralized joint control. A high-speed serial bus (SERCOS) connects the joints with the main computer. The only additional external connections are the power supply wires for the electronics and the motor.

4 Medium-Term Space Robotics Missions

There are three space robotics missions envisaged for the near future, ROKVISS (Robotics Component Verification on ISS) and TECSAS (Technology Satellite for Demonstration and Verification of Space Systems). A first business case for OOS will be the SLESTTM (Spacecraft

Life Extension System), where a lot of know-how, gained from the previous missions and studies, will be directly applied.

4.1 ROKVISS

ROKVISS will demonstrate and verify DLR's light-weight robotics components under realistic mission conditions. The most interesting operational mode will be direct haptic tele-manipulation, to show the effectiveness of tele-presence methods for further satellite servicing tasks. Tele-presence can be characterized as an advanced concept of tele-manipulation: the robot in space is directly operated by a human within a closed-loop-control mode to perform remote manipulations like being present in space while physically being on ground. For high fidelity tele-presence the human operator must feel as if he/she is being present at a distant location and interpret the mechatronic manipulator as a natural extension to his/her own body. This suggests that the human operator receives input to (almost) all the human senses (vision, hearing, haptic, sense of smell and degustation) and commands the tele-operator in a nearly natural way by demonstration. The last two senses (smell and degustation) have no practical evidence at present, due to the lack of sensors and actuators to measure and display them.

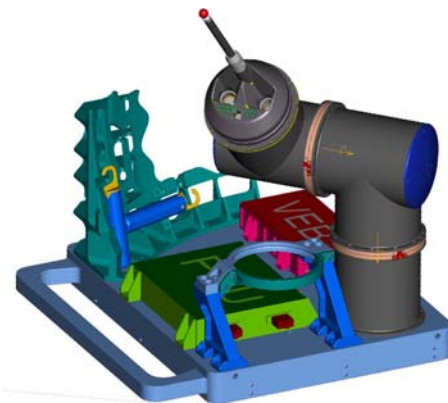


Fig. 4 ROKVISS 2-Joint Manipulator

For tele-presence mode demonstration and verification, stereo video images in conjunction with the current robot joint and torque values will be fed back as the current situation to the ground operator. The operator controls the slave robot at the remote site via a force-feedback-control device. Using high-rate up- and downlink channels, the operator will be directly involved into the control loop. Crucial factors in gaining a high quality immersion of the operator into the remote scenery are high-rate, low-latency (less than 500 ms) and jit-

ter-free force/position data, and a reasonable good and up-to-date stereoscopic video transmission. The tele-presence mode can only be used for several minutes during the phase of direct radio contact, when the system passes over the tracking station in Germany (German Space Operation Center, GSOC).

In automatic mode, the system goes through predefined motion sequences. Herein, the measured joint and sensor data will be stored on-board and transmitted to ground during the next possible contact phase.

Tele-Presence Mode Experiments:

Besides typical force-controlled contour-following tasks, the following experiments will be executed to verify the various constraints of direct force feedback:

- To verify the impact of e.g. varying time delays within closed-loop controlled systems a virtual spring is emulated by the joint control system. The operator has to follow a predefined virtual path which fades in into the video display. While performing this task the robot is fixed at its position. The difference between the current and the commanded robot position describes a virtual spring, whose deflection will engender the feedback forces to the operator.
- To verify the impact of external energy storage within the closed-loop control link, the operator drives the stylus within one of the open ended spanners, which are connected to a real spring. These spring elements () are also applied to verify the gear friction model.

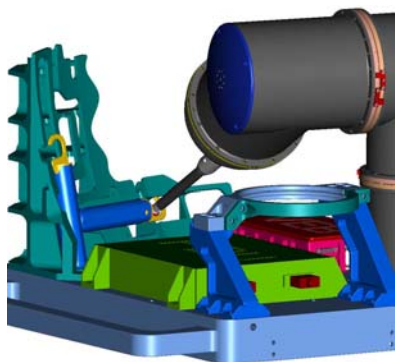


Fig. 5 ROKVISS Spring device

- To verify the impact of time delay, some experiments will be performed with varying simulated time delays, whereas a round trip time of approx. 500 ms is representative for operations in LEO via a data relay satellite in GEO.

The main purposes of the **automatic mode experiments** are:

- the long-term verification of the joints' behavior during free space operation as well as

- the dynamic parameter identification under space conditions.

The same experiments will be conducted several times during the entire mission. The automatic mode experiments will be activated via the mission timeline, independently of direct RF contact. All joint parameters are stored on the on-board storage device and transferred to ground on demand during the next possible radio contact phase.

For the design of joint level controllers (position, torque, and impedance control), efficient and reliable autonomous off-line identification methods have been developed, which provide the stiffness and damping, as well as the friction parameters. These identification methods will be used for the parameter estimation of robotics systems under real mission conditions.

The Canadian Space Agency uses ROKVISS to study how the space environment affects the behavior of bodies interacting together in a contact situation. Specifically, the project proposes to measure the energy dissipation occurring during intermittent impact events, as well as the frictional forces acting between two bodies.

4.2 TECSAS

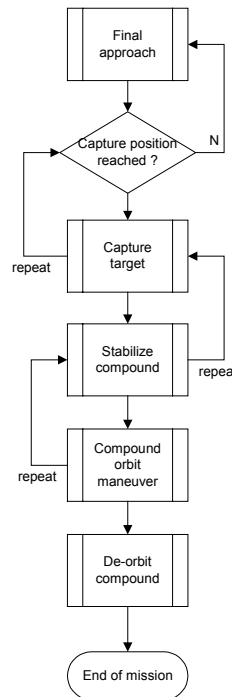


Fig. 6 Mission-Phases

The goal of TECSAS is the on-orbit verification of key robotics hard- and software elements for advanced space maintenance and servicing systems. An international project team composed of EADS, Babakin Space Center and DLR-RM performed the national financed phase A study in 2003. It is planned to launch a target and a chaser satellite, whereas the chaser is equipped with a seven axis robot arm and a gripper system. The Russian Multi-Purposes Orbital Boost Platform is envisaged as the base module for chaser and target. For docking and capturing operations, a ROKVISS based robot arm will be used as well as MARCO as the overall

control system. The mission consists of the following phases (Fig. 6): far rendezvous, close approach, inspection fly around, formation flight, capture, stabilization and calibration of the compound, compound flight ma-

neuver, active ground control via tele-presence, passive ground control during autonomous operations (monitoring), and controlled de-orbiting of the compound. Robotics is highly involved in capture, stabilization, orbit maneuvers and de-orbiting. The main objective of the capture experiment is to investigate different control strategies and AOCS control modes, as well as to determine suitable maneuvers for soft docking and the subsequent stabilization of the chaser-target spacecraft compound.

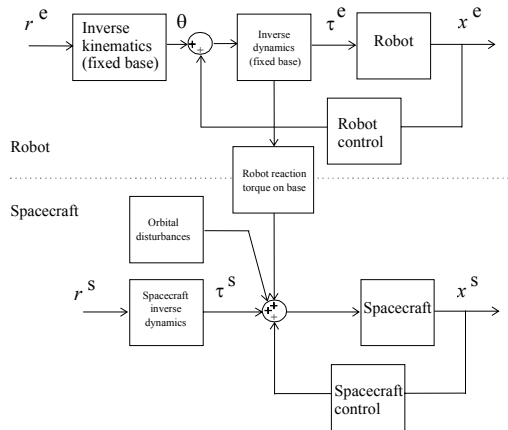


Fig. 7 Command position (r^e) relative to the inertial reference, AOCS compensates disturbances

Two major control strategies are possible for the chaser spacecraft: free-flying or free-floating. In the first case, the AOCS intervenes to limit or eliminate any spacecraft motion (therefore the spacecraft can be kept stationary in the operational space), while in the second

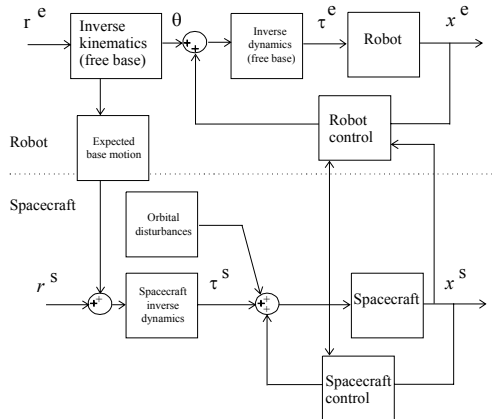


Fig. 8 Command position (r^e) relative to the inertial reference and allow for base motion. If the spacecraft moves out of the allowed operating window, compensate for it with the spacecraft control.

case the spacecraft is allowed to move in reaction to the robot movements. While the first case (Fig. 7) is more simple to tele-operate and may be necessary to fulfill spacecraft motion constraints (e.g. attitude motion may be limited for communication purposes), the second case

(Fig. 8) is more interesting for reducing fuel consumption for spacecraft control and is more safe, since jerky motions arising from thrusters are avoided.

The chaser will be navigated into the vicinity of the target satellite. A number of images will be taken automatically and dumped to the ground segment. They show the relative position between both spacecrafts and assist to estimate the target motion by the ground operator or by the ground station's control software. After this phase the chaser moves closer towards the target to have the structure element to be grasped within the workspace of the manipulator.

- **In tele-presence mode**, the ground operator will position the gripper in front of the structure element by means of stereo video information. After closing the gripper, the compound stabilization takes place.
- **In automatic mode**, the ground operator selects the structure element to be tracked by means of image processing and enables the automatic capturing, thereafter.

Note that the image processing is done on-ground, thus the vision control loop is closed via the up- and down-link channel (same principle as tested in ROTEX). In automatic mode, it is assumed that the commanded motion of the robot is determined by a motion planning algorithm. This is necessary to verify the feasibility of the grasping maneuver, in terms of robot dynamic (actuator) and geometric (collision avoidance) constraints. The motion planning solution, based on the predictive simulation of the target, provides a joints motion sequence which

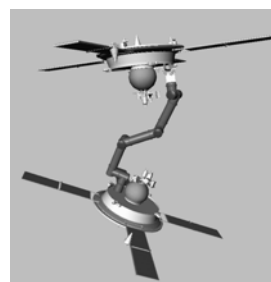


Fig. 9 Capture Position

minimizes some predefined cost criterion (e.g. execution time, spacecraft fuel consumption, preferred grasping configuration for subsequent stabilization).

Dynamic singularities of a free-floating robot are an important issue, too. They are path dependent in operational space, but fixed in joint space, and also dependent on the inertial parameters. If a path planner is used to determine the motions of the robot, the singularities are automatically avoided, since the algorithm works in joint space. However for tele-presence, a supplementary algorithm is necessary to inform the operator if a singularity is being approached. A workspace analysis can be performed to determine the singularity-free workspace, in which the operator can move

safely [6]. After closing the gripper, a stabilization motion has to occur to eliminate the residual relative velocity between the two satellites. A good means to damp this motion is to make the robot compliant for the capturing moment and increase the stiffness slowly until a stable compound is achieved. The motion damping in tele-presence mode will also be investigated, where the operator tries to damp the motion by means of tactile and visual feedback.

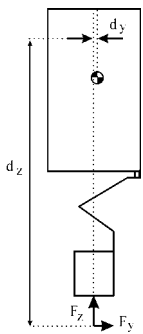


Fig. 10 F_y accounts for displacement d_y

During orbit- and de-orbiting maneuvers the chaser will push the target rather than pull it, to avoid damage by the thrusters gas exhaust. The chaser thrust force must then not only act in the direction of travel but also through the center of mass of the compound (Fig. 10). If this is not so, the whole compound will rotate about its center of mass. The robot will play an active role in order to direct the thrust force correctly through the common center of mass and to achieve the required posture.

4.3 SLES, CX-ORS

Orbital Recovery Ltd. [7] has initiated its so-called Spacecraft Life Extension System (SLES™) which will significantly prolong the operating lifetimes of valuable telecommunications satellites. The SLES will operate as an orbital tugboat, supplying the propulsion, navigation and guidance to keep a telecommunications satellite in its proper orbital slot for many

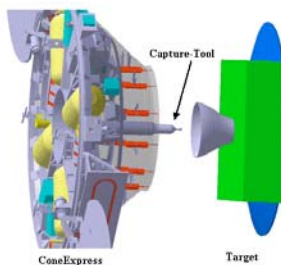


Fig. 11 SLES System

additional years. Another application of the SLES could be the rescue of a spacecraft that have been placed in a wrong orbit, or which have become stranded in an incorrect orbital location. SLES will rendezvous with the telecommunications satellite and link up using DLR's proprietary capture tool that connects to the telecommunication satellite's apogee kick motor, as proposed within the ESS technology study. Apogee kick motors are used by nearly every telecommunications satellite, and they provide a strong and easy to access interface point.

DLR's capture tool will be used in conjunction with control strategies, gained from ESS and GETEX, to perform the final approach and docking phase, whereas

Dutch Space will be responsible to build the satellite (ConeExpress) and to conduct the far approach (Fig. 11).

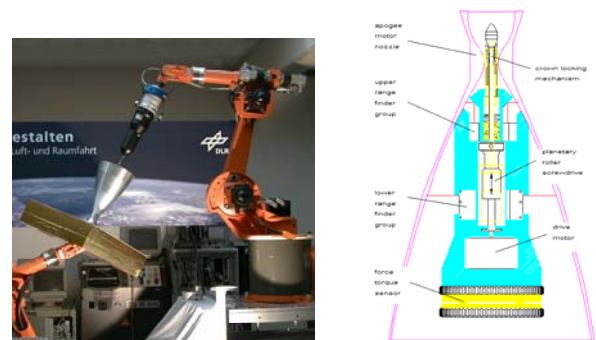


Fig. 12 HIL-Simulator & Capture Tool

The HIL simulator (Fig. 1 & Fig. 12) will be applied to verify and demonstrate the feasibility of the mission as well as for operator training.

5 Conclusion

We have outlined the long-term space robotics projects as well as recent results in DLR's robotics lab. These hardware and software concepts could pave the way to a long-term applicability of robots in space, and to make OOS more economic and common.

6 References

- [1] G. Hirzinger, B. Brunner, J. Dietrich, J. Heindl, *ROTEX - The First Remotely Controlled Robot in Space*, IEEE Int. Conf. on Robotics and Automation, San Diego, CA, May 8-13, 1993
- [2] G. Hirzinger, K. Landzettel, Ch. Fagerer, *Teletrobotics with large time delays- the ROTEX experience*, IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS), Munich, Sept 12-16, 1994
- [3] K. Landzettel, B. Brunner, K. Deutrich, G. Hirzinger, G. Schreiber, B.-M. Steinmetz, *DLR's Experiments on the ETS VII Space Robot Mission*, Proc. of the 9th International Conference on Advanced Robotics (ICAR'99), Tokyo, October 25-27, 1999
- [4] M. Oda, K. Kibe, F. Yamagata, *ETS-VII Space Robot In-Orbit Experiment Satellite*, IEEE Conf. on Robotics and Automation, Minneapolis, April 1996
- [5] Eckard Settlemeyer, Ralf Hartmann, K. Landzettel, Erich Lehl, Winfried Oesterlin, *"The Experimental Servicing Satellite ESS"*, 21th, ISTS Conference 1998, Omiya, Japan
- [6] Cusumano, F., Lampariello, R., *"Development of tele-operation control for a free-flying robot during the grasping of a tumbling target"*, DLR report 515-04-02, March 2004
- [7] <http://www.orbitalrecovery.com>