DEVELOPMENT AND APPLICATIONS OF SPACE ROBOTIC MANIPULATION TECHNOLOGY AT DLR

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ABSTRACT

Orbital servicing missions aiming for operations such as life extension, repairing, or upgrading a client satellite, require the use of a manipulator arm operating on a controlled satellite base. For On-Orbit Services (OOS), the arm performs multiple tasks, including the approach, grasping and stabilization of the target (cooperative or not). Later, the docking maneuver begins and allows the connection of the two satellites through a dedicated interface, hence an OOS task or a de-orbiting maneuver can be performed on the combined structure. After docking or berthing the arm is free to perform activities such as inspection, refueling, repairing and servicing.

DLR has been developing robotic manipulation technologies for over three decades, successfully working both on hardware (robotic manipulators and grippers) and software (torque and compliant control, as well as motion, task and assembly planning). This paper provides an overview of such developments, discussing some design aspects as well as mission requirements and operational considerations.

Keywords: space robotics, robotic manipulation, robotic arm, orbital services

1. INTRODUCTION

DLR's heritage in developments and missions starts with the ROTEX experiment in 1993, a small six-axis robotic arm launched aboard the D2 Space Shuttle mission to perform grasping of a free-floating object using various control modes [1]. The technology and insights from this mission were used to evolve the design of the DLR Lightweight robot arm, which was later licensed to KUKA for commercial production of the pioneer KUKA Lightweight Robot arm [2]. Applications in space were followed by ROKVISS, a two-joint arm mounted outside the ISS for more than five years, used for testing the long-term performance of a robot in real space conditions [3, 4, 5]. DLR has continued the development of robotic manipulators based on its pioneer torque-controlled technology, both for ground and for space applications. The latest space robot from DLR, the CAESAR robotic arm, is a lightweight, compliant and fully redundant seven-joint manipulator designed for on-orbit operations [6].

The robotic arm heritage of DLR has been used in diverse OOS studies, including DEOS (Deutsche Orbitale Servicing Mission) and e.Deorbit. The same technologies used in OOS can be extended for on-orbit robotic assembly to construct large space structures directly in space, hence reducing costs and complexity. Recent projects sponsored by the EU Comission have explored feasibility of this type of applications, including PULSAR (Prototype of an Ultra-Large Structure Assembly Robot), MOSAR (Modular Spacecraft Assembly and Reconfiguration), ASCEND (Advanced Space Cloud for European Net zero Emission and Data sovereignty), and also the ESA project MIRROR (Multi-arm Installation Robot for Readying ORUS and Reflectors). Now, the CAESAR arm and technology derived from it are involved in the two major European orbital servicing missions: EROSS (European Robotic Orbital Support Services), sponsored by the EU Comission, and RISE, sponsored by ESA.

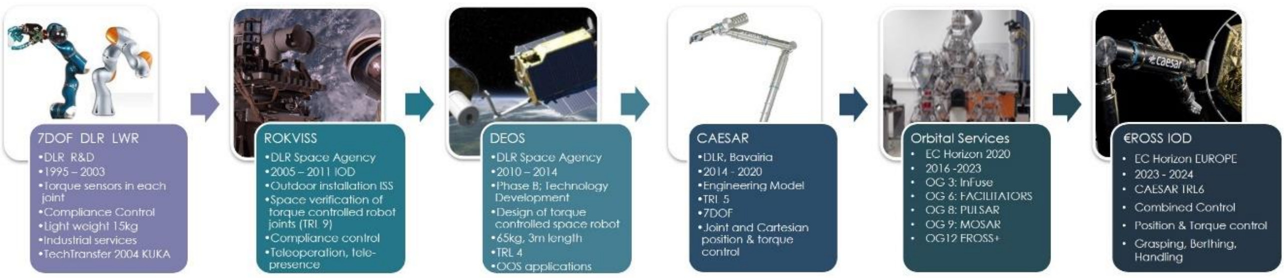

Figure 1. Evolution of space robotic arm development at DLR.

2. ROTEX Spacelab mission (1993)

ROTEX (Robot Technology Experiment) was the starting shot for Germany's participation in space automation and robotics [1]. It contained as much sensor-based on-board autonomy as possible, but on the other side it presumed that for many years cooperation between man and machine, based on powerful telerobotic structures, would be the foundation of high-performance space robot systems, operable especially from ground. Thus, ROTEX tried to prepare several operational modes, such as telemanipulation on-board/on-ground as well as tele-sensor-programming from ground. It flew with the Spacelab-Mission D2 in 1993 and performed several prototype tasks, e.g. assembling a truss structure and catching a free-floating object, in different operational modes, e.g. off-line programmed, but also on-line teleoperated from ground by combining man and machine intelligence.

In order to demonstrate servicing prototype capabilities three basic tasks were performed:

- Assembling a mechanical grid structure
- Connecting/disconnecting an Orbital-Replaceable-Unit (ORU) using a bayonet closure
- Grasping a floating object.

The verified operational modes were:

- Automatic, i.e. preprogramming on ground,
- Teleoperation on-board, i.e. an astronaut controlled the robot using stereo-TV-monitor,
- Teleoperation from ground using predictive computer graphics, by a human operator supported by machine intelligence,
- Tele-sensor-programming, i.e. learning by showing in a completely simulated world on-ground, including the sensory perception, with sensor-based execution later on-board.

Figure 2. ROTEX arm and gripper. Credit: DLR.

3. ROKVISS flight mission (2005-2010)

In the mid-nineties DLR developed a new generation of light weight robots (LWR) with an excellent power to weight ratio as well as impressive control features, which made the system easy to use and safe for terrestrial servicing application [2]. This technology was transferred to the robot manufacturer KUKA, which transitioned this pioneering technology into a commercial product, the KUKA iiwa robot, spearheading the area of collaborative robotics.

The same hard- and software technology was adapted for space, modified and verified in the project ROKVISS (RObotic Components Verification on the ISS). The robotic arm was mounted on the ISS on January 26, 2005 during a six-hour spacewalk. The astronauts attached a universal platform to the outer wall of Zvezda, the Russian service module, on which ROKVISS was then installed. The system was operated in space for five and a half years (2005–2010) and successfully passed around 500 tests [3].

Figure 3. Mounting of the ROKVISS on the ISS. Credit: RKK-Energija.

The system basically consists of a robotic arm with two joints, a "metal finger" at the tip of the arm, a stereo video camera and a mono camera. The universal platform also holds boxes with electronics for power distribution and image processing, as well as a special contour used for dynamic robot movement experiments and for experiments to determine joint parameters. The robot joints and the cameras are controlled by a central experiment computer inside the ISS.

Radiation posed a major challenge because the frequent ion bombardment could damage electronic components. To prevent damage to these components in the joints, their modules have an integrated system ensuring that the power supply is automatically switched off at the moment of a short circuit, and the stored energy is eliminated. Due to the extreme temperature fluctuations, the robot joints had to withstand temperatures between minus 20 to plus 60 degrees Celsius.

The aim of ROKVISS was to test and verify new robot hardware and powerful control concepts in realistic mission operations [4]. After successfully completing all the scheduled tests, DLR completed a big step in the development of new types of lightweight robots for cost-effective use in space and their convenient remote control from Earth.


Fig. 4. ROKVISS experimental setup. Credit: DLR.

The robotic arm could operate in two different modes. Automatic mode was used during phases when there was no radio connection to the ground. The experiments were controlled by the experiment computer onboard the ISS, and the experimental data were saved for later evaluation. The direct involvement of a human operator in the control loop was tested for repair and maintenance tasks on satellites. Therefore, a teleoperation mode had to be provided, which gave the operator the feeling they were doing the work directly at the remote location [5]. In telepresence mode, the robot arm was controlled remotely directly from ground during the overflight via the transmitting and receiving antenna in Weilheim (southern Germany). For the first time, a robot in space was controlled from earth without any significant time delay – a novelty in space robotics. In the other direction, the scientist operating the robot arm on earth received visual and sensory feedback on the actions of the robot arm with only a minimal time delay.

4. DEOS orbital service study (2009-2014)

DEOS (Deutsche Orbitale Servicing Mission), funded by the German national space agency (DLR), was a precursor for operational missions conducting On-Orbit Servicing and Assembly, robotic inspection, maintenance and assembly of infrastructure in orbit, and carrying out orbit maintenance and maneuvers on other satellites including the controlled de-orbiting of other satellites.

The primary goals of the DEOS mission were:

- Capture of a tumbling and non-cooperative satellite
- Intentional de-orbit (controlled disposal) of the coupled set of satellites (Client and Servicer)

Secondary goals of the DEOS mission relating to technology demonstration and verification were:

- Test and evaluation of several methods for capturing a non-cooperative tumbling satellite by means of a robotic arm
- Using telepresence operations and having the Servicer attitude controlled
- Using telepresence operations and not controlling the Servicer attitude (freely drifting Servicer)
- Using autonomous operations and having the Servicer attitude controlled
- Using autonomous operations and not controlling the Servicer attitude (freely drifting Servicer)
- Capture a satellite with controlled attitude via docking
- Design of the Servicer for highly autonomous operations, to allow its operations without ground support.
- Demonstration of a relevant maintenance task or assembly tasks on the Client Satellite, e.g. exchange of an orbital replaceable unit (ORU), refueling.

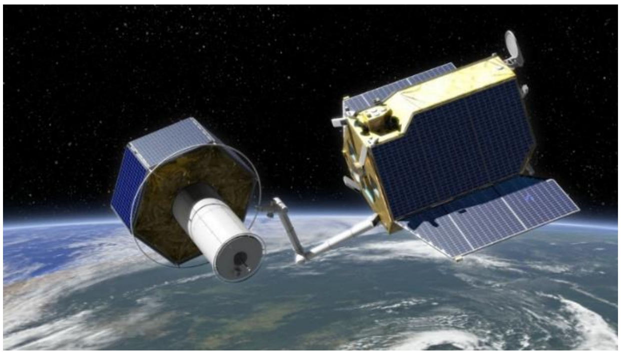
Fig. 5. DEOS – Orbital Simulation. Credit: Airbus Defence & Space.

The robotic arm (manipulator) consisted of seven modular, torque-controllable joint elements based on DLR’s light weight manipulator design, as space-qualified within the ROKVISS mission. This 7-joint arrangement provided kinematic redundancies in order to avoid joint singularities during the capturing or servicing process. The arm had to have a sufficient minimum length to allow all tasks to be performed with the Client in any position and spinning or tumbling state. Extensive analysis showed that an arm length of 3m was a good compromise fulfilling the different requirements. During launch the arm should be folded and attached to the Servicer spacecraft outer structure.

After successfully passing the PDR (Preliminary Design Review) in 2014, the German national project DEOS was discontinued.

5. CAESAR robot arm

The Institute of Robotics and Mechatronics (RM) at DLR continued the work on on-orbit servicing that began with DEOS, despite its cancellation. This derived in the creation of CAESAR, the new space service robot arm, designed to provide a multi-purpose manipulation system capable of performing different tasks on cooperative and non-cooperative targets.

The CAESAR design requirements are driven by use-cases in Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO). Nevertheless, the design of CAESAR is advanced by DLR RM independent of, but aligned with existing missions. The robot is at the stage of an Engineering Model (EM), demonstrating and assuring flight readiness within the time frame of future space missions. Within EROSS, one of such missions, the robot is at the EQM level for qualification for an orbital services mission in LEO.

The key to CAESAR's high performance is its intelligent impedance and torque/position-controlled joints. Each joint is a building block for setting up diverse robot kinematics depending on the different mission goals. The scalability of the robot is determined by the number of joints and the length of the links. CAESAR's seven DoF (Degrees of freedom) enable it to meet different dexterity and kinematic redundancy requirements. Extending the impedance controller, the CAESAR arm can behave compliantly, while maintaining TCP position. The compliant behavior is triggered if any part of the robot detects contact with the environment. Compliance is a significant safety feature in dynamic environments or in close vicinity to the astronauts.

In addition, the production and qualification of the system has to be efficient and accurate to ensure commercial success and confidence in operation. The robot system is adaptable to various carriers and different types of satellites or spacecrafts, and qualified for each specific mission profile to guarantee maximum compatibility with mission requirements.

Figure 6. CAESAR robot arm. Credit: DLR (CC BY-NC-ND 3.0).

6. TINA

TINA was a smaller robotic manipulator developed for missions requiring a small modular arm in space. With a length range of 30cm to 2m, it is ideal for use on small satellites in ISAM (In-Space-Assembly-Manufacturing) applications, for supporting and collaborating with astronauts in space stations, and for exploring the Moon and Mars.

The electronics of the TINA arm are based on the Universal Motor Controller (UMC), which had already been used in the successful MASCOT space project. The mechanical joints of the arm are based on the design and findings of the ROKVISS robot.

TINA was the technological basis of the ESA STABLE project. In the course of this project, DLR developed a so-called Breadboard model of the arm for the Mars Sample Transfer Lander [7].

Figure 7 Stable: DLR Space Arm Technology mounted on a lander to demonstrate autonomous work. Credit: DLR (CC BY-NC-ND 3.0).

The Breadboard comprises an arm of 2m length mounted on a lander. The arm was equipped with a gripper from OHB and several cameras to enable visual serving. The goal of the project was to demonstrate sample retrieval and storage of soil samples in Mars, all performed in a fully autonomous mode.

7. FEASIBILITY STUDIES

The work of DLR in space robotic manipulation has been used for different mission feasibility studies sponsored by the ESA (e.Deorbit, COMRADE) or by the European Comission (PULSAR, ASCEND).

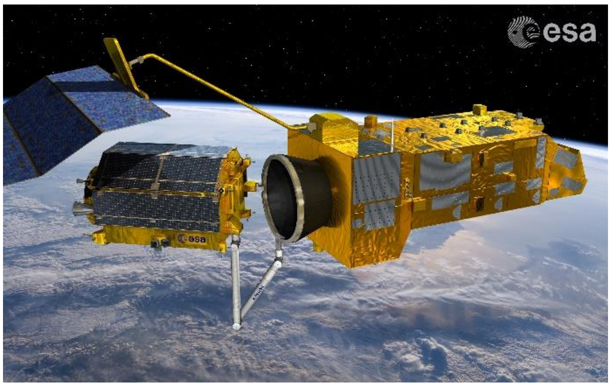

Figure 8. e.Deorbit's robotic arm. Credit: ESA.

- **e.Deorbit** [8]. An ESA-sponsored project, with the main goal of analyzing the removal of ENVISAT, an eight-ton Earth-monitoring satellite that is defective and free-tumbling in space since 2012. The capture was analyzed considering a grasping point on the Launch Adapter Ring (LAR), which provides a solid and stiff attachment point. The capture was intended with a seven DoF robotic arm, endowed with a two-bracket gripper.

- **COMRADE** (COntrol and Management of Robotics Active DEbris removal) [9] was an ESA-sponsored study with the objective to design, develop, and test the control system of a robotic spacecraft, i.e. a servicing spacecraft equipped with a manipulator, tasked to perform an Active Debris Removal and a refueling mission. The identified technical challenges were: Control of uncertain coupled dynamics of spacecraft platform, robotic manipulator, and end-effector; synchronization with fast tumbling targets, and limitation of structural loads on arm. DLR's impedance controllers for the manipulator have been tested on the OOS-SIM facility considering the servicer in a free-floating mode to grasp and stabilize the client satellite using semiautonomous or telepresence mode [10]. The OOS-SIM has been used for verifying the coordination strategies between the arm and GNC system. This platform was employed in the ESA COMRADE project for the on-ground validation of control algorithms for grasping the ENVISAT satellite.

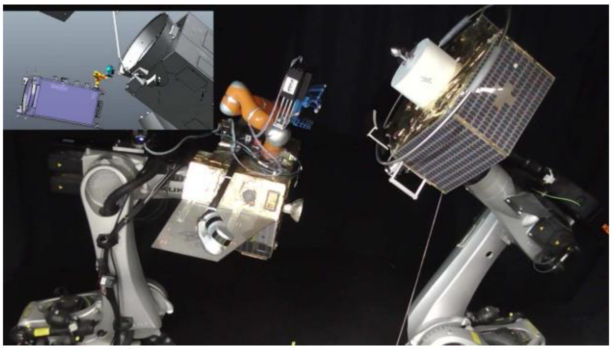

Figure 9. OOS-SIM facility composed of servicer robot (left) equipped with a light-weight manipulator arm and client robot (right). Top-left: the simulated space scenario for the capture of Envisat in COMRADE.

- **PULSAR** (Prototype of an Ultra Large Structure Assembly Robot) [11] was a project sponsored by the EU Comission, intending to verify on ground the feasibility of assembling the primary mirror for a space telescope using autonomous robotic technologies. Three different demonstrators were considered: one for showing the robotic assembly task, one underwater demonstration of simplified assembly, and a simulator-based analysis of the mission. DLR implemented the simulator for precise assembly of mirror tiles using a KUKA mobile robot with a robotic arm mounted on top. The simulator successfully demonstrated the autonomous assembly of the mirror using a combination of adaptable perception, integrated assembly and motion planning, and compliant control of the robotic manipulator.

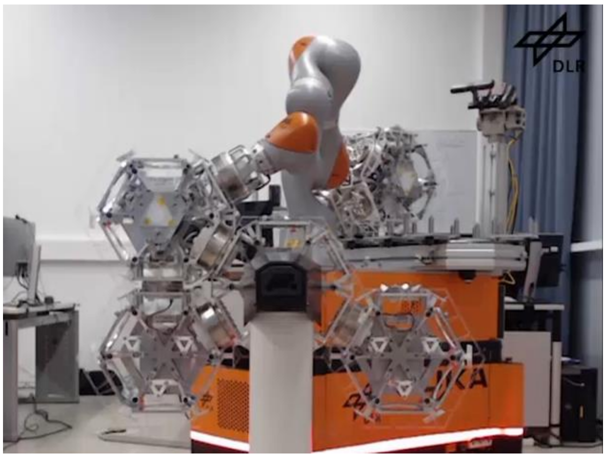

Figure 10. PULSAR: mobile robotic manipulator performing the assembly of a primary mirror. Credit: DLR.

- **ASCEND** (Advanced Space Cloud for European Net zero emissions and Data sovereignty) was a project sponsored by the EU Comission, intending first to assess if the carbon emissions from the production, launch and operation of a space-based data center is significantly lower than the emissions generated by ground-based data centers, therefore contributing to the achievement of global carbon neutrality. The second objective was to prove that it is possible to develop the required launch solution and to ensure the deployment and operability of these spaceborne data centers using robotic assistance technologies currently being developed in Europe in missions such as EROSS.

Figure 11 ASCEND data center in space. Credit: Thales Alenia Space.

8. EROSS

EROSS, standing for European Robotic Orbital Support Services, is the flagship European mission for performing orbital services, including the capture of a prepared and an unprepared cooperative client for performing inspection, refueling and repairing tasks [12]. The robotic subsystem comprises among others DLR's robot arm CAESAR, a standard interface by Space Application Services, the LARIS gripper from PIAPS, robot vision system from Thales-Alenia-Space, and additional software components from GMV and SINTEF.

The project is currently at the C1 stage. The engineering model of the CAESAR robotic arm is located at DLR's lab, integrating the above-mentioned partner components. The purpose of the setup is to perform a full functional testing of the robotic operations for the mission. Additionally, an EQM model is currently under preparation for the testing and qualification campaign to verify the fulfillment of the corresponding mission requirements.

Figure 12. EROSS: CAESAR arm performing the capture of an unprepared client. Credit: DLR.

9. CONCLUSIONS

Meanwhile it is common sense, robotics for in-space operations and services is a key technology to enhance the performance, resilience and sustainability of space assets. This includes satellite servicing, assembly, manufacturing, recycling and active debris removal.

Many different technologies have to be combined for successful in-space services. This includes robust hardware development, demanding software requirements and a close, trustful cooperation of the different disciplines like space engineering and robotics.

DLR's contributions to space robotics began in 1993 with the ROTEX experiment, followed by the ROKVISS experiment, where a two-joint robot arm was tested in the harsh real space conditions outside the ISS. DLR's latest space robot offering, the CAESAR robotic arm developed in 2018, is a lightweight, compliant and fully redundant 7-joint manipulator designed for performing on-orbit operations.

An overview of the advancements made by the DLR's Institute of Robotics and Mechatronics in orbital manipulation over the past 30 years is provided in the Youtube video [13]. DLR continues leading the development of space robotic technology for space sustainability.

10. ACKNOWLEDGEMENTS

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