9.2 Other General Software and Hardware Technology Developments

The mission activities go hand in hand with technology developments. In the COMRADE project, ESA has promoted the design, development and testing of a control system for a free-flying robot for two missions: (a) Active Debris Removal (ADR) with a dedicated 7 DoF robotic manipulator and LAR gripper end-effector. (b) Refueling mission (see also Section 9.3) Here, a combined controller was tested on the OOS-SIM facility for the capturing of ENVISAT. The controller ran on a LEON4 computer, proving its applicability for space flight. Furthermore, an overview of the design and outcomes of the project were presented in (Colmenarejo, et al., 2018), to include a comparison between a robust $H\infty$ controller and a nonlinear Lyapunov-based controller. The results from Monte Carlo simulations showed that although the $H\infty$ controller performed better in meeting the given velocity requirements, the nonlinear controller was usually able to achieve a stable and successful grasp in presence of contact. The nonlinear controller was also presented in detail in (De Stefano, Mishra, Giordano, Lampariello, & Ott, 2021), including results from experiments performed on DLR's OOS-SIM experimental facility.

Other important software and hardware developments have been undertaken in Europe under the six-year PERASPERA project (PERASPERA, 2014), within the EU Strategic Research Cluster on Space Robotics, aiming, among other things, at the maturation of orbital robotic technologies. The first set of grants (Operational Grants) within this project (2016-17) was dedicated to the development of common building blocks, to include an operating system or middleware (European Space Robot Control Operating System, ESROCOS), a planning framework (European Robotic Goal-Oriented Autonomous Controller, ERGO), a sensor data fusion framework (InFuse), an integrated sensor suit (I3DS) and a standard interface for robotic manipulation of payloads (SIROM).

Running at the DLR since 2014, the RICADOS project aims at holistic simulation of an on-orbiting servicing mission, from a realistic ground segment (GSOC), to a communication link to a space segment, performing inspection, rendezvous and capture tasks (Benninghoff, et al., 2018). These tasks are partly validated on DLR's hardware-in-the-loop facilities EPOS and OOS-SIM. Furthermore, the DLR, in cooperation with the MIT, is promoter and developer of a demonstration mission with the ASTROBEEs on the ISS, for the approach maneuver of a chaser satellite to a tumbling target. In this mission, the functional sequence motion prediction, motion planning and robust trajectory tracking will be demonstrated (Albee, et al., 2021). The telepresence technology has also been extensively demonstrated by the DLR in different projects, to include KONTUR-2 (Artigas, et al., 2016) (Riecke, et al., 2016) and METERON (Schmaus, et al., 2018).

The initial PERASPERA building blocks were then used in a second set of grants, which developed concepts and technologies for a servicing mission (EROSS), for modular spacecraft assembly and reconfiguration (MOSAR) and for on-orbit assembly of a large space telescope (PULSAR). The goal is to perform an orbital demonstration mission in 2023-24.

In particular, the EROSS project assesses and demonstrates the capability of a manipulator-equipped servicing spacecraft to perform medium and close-range rendezvous, and then to capture and manipulate/ service a collaborative client satellite with a highest degree of autonomy, see Figure 11. EROSS reuses and integrates both software (such as ESROCOS, ERGO and INFUSE) and hardware (such as SIROM), developed in previous Operational Grants led in PERASPERA, and previous developments on projects by the European Space Agency, such as the ASSIST project. However, when required, new developments are also made, such as a new gripper for the manipulator. To facilitate the varying demands of the different stages of the mission, a versatile GNC architecture is developed, including a Coordinated Control scheme that allows for the simultaneous Model-based PD control of the servicer platform attitude and Compliant Control of the end-effector of the 7 Dof manipulator (Dubanchet, et al., 2020).

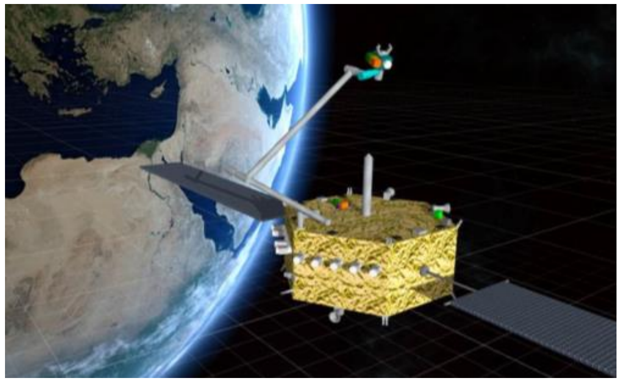
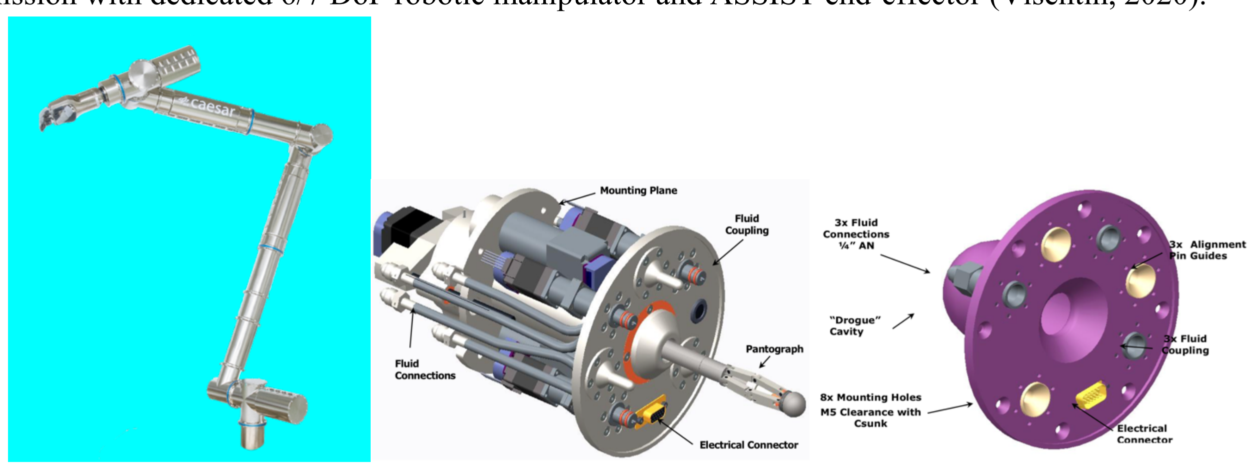


Figure 11. The EROSS Concept includes a free-flying S/C equipped with a 7-DoF manipulator (EROSS EU Horizon 2020).

9.3 Arms, Grippers, and End-effectors

The development of hardware for orbital robotics has also been very active in the last years. The DLR had tested and validated its robot joint technology in the ROKVISS mission (Yoshida, Wilcox, Hirzinger, & Lampariello, 2016), in which two robot joints were placed on the outer surface of the ISS, between 2005 and 2011. In a recent development, this technology has been improved and used to build a seven-degree of freedom robot manipulator, the Compliant Assistance and Exploration SpAce Robot (CAESAR), shown in Figure 12a (Beyer, et al., 2018). Other robotic arms are being developed in the USA, to include DARPA's FREND arm, as well as the Dragonfly, later developed into the longer SPIDER. A torque-controlled robot is also constructed by TUI with the name of KRAKEN.

ESA focused on developing a cost-effective solution for refueling GEO satellites in space as currently the fuel levels often deplete, in particular for communications satellites, while the payloads are still in good health. A refueling mechanism was developed, called ASSIST, which will allow satellites in the future to be refueled and serviced while on orbit, extending their life, Figure 12b. As is typically the case for most end-effectors, the ASSIST mechanism performs first *soft docking* (allowing relative motions but not separation) followed by a motorized retraction ending during a *hard docking* phase (rigidization) using aligning pins (Medina, et al., 2017). ASSIST is the reference mission with dedicated 6/7 DoF robotic manipulator and ASSIST end-effector (Visentin, 2020).



(a) (b)

Figure 12. (a) CAESAR robot arm with SpaceHand (DLR), (b) ASSIST mechanism for refueling satellites (ESA).