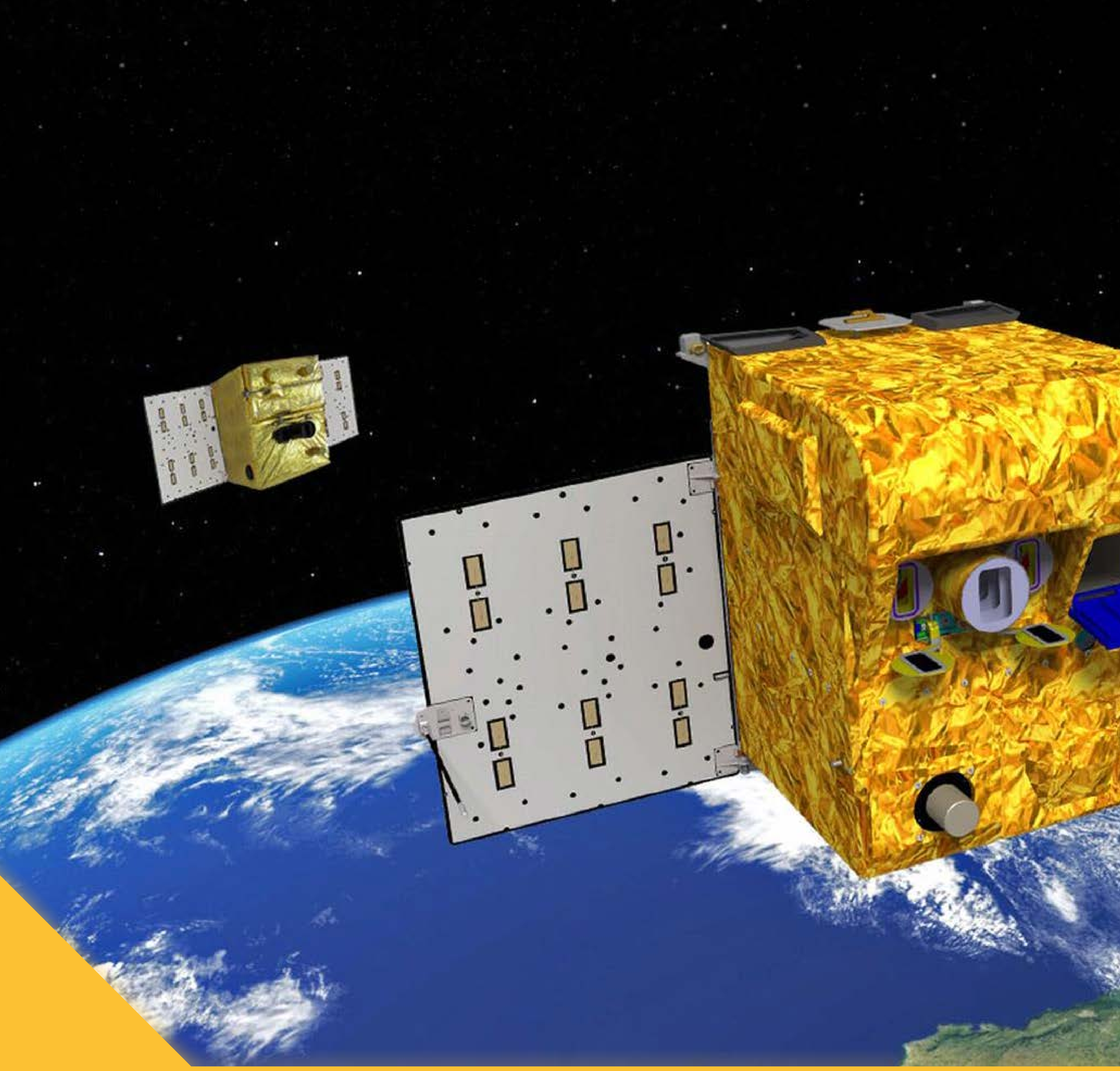
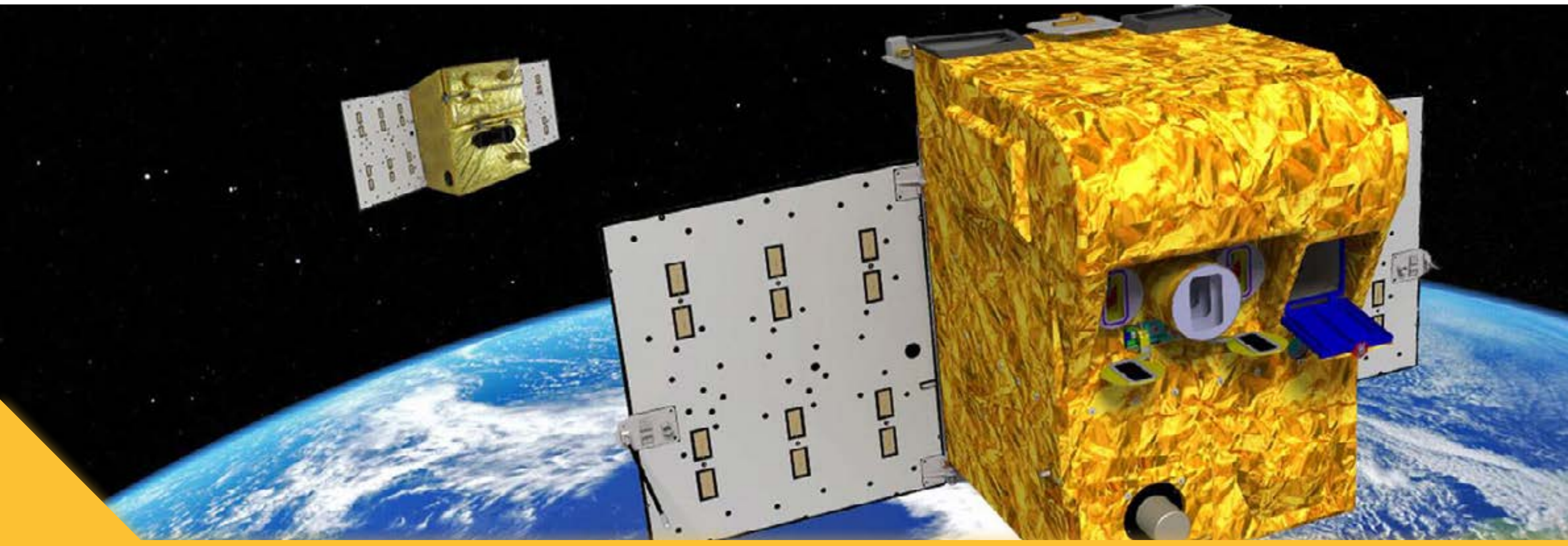


On-Orbit Servicing Technologies



On-Orbit Servicing Technologies

On-Orbit Servicing (OOS) describes a service in space where a satellite, part of a satellite or in general a structure is maintained, repaired or extended. A prominent example is the correction of the optics of the Hubble space telescope in 1993 by astronauts. Present and future on-orbit servicing missions focus on automated, for example robotic based, service tasks. One exemplary application is the extension of the life-time of satellites like the Mission Extension Vehicle, a OOS mission of Northrop-Grumman. The idea is to take over the orbit and attitude control of a client spacecraft in the geostationary orbit and to perform station keeping, relocation and final disposal to a graveyard orbit.

Re-fueling of a satellite is another example of a service task, planned for the Restore-L mission of NASA.

Apart of lifetime extension, on-orbit servicing comprises also debris removal missions. Typical targets are non-operative satellites or debris objects like upper stages of carrier rockets. An exemplary mission is the planned Clearspace-1 mission of ESA where a chaser will target the upper stage of the Vespa (Vega Secondary Payload Adapter) in Low Earth orbit.

These new classes of missions are very challenging and require a number of new technologies for inspection, approach (called rendezvous), capturing and last but not least for the final maintenance or removal service. There is already long experience in the field of rendezvous and docking of supply vehicles to cooperative targets like the International Space Station. Further, many formation flying missions with cooperative spacecraft have been executed. On-orbit servicing missions however deal with targets which are neither developed for rendezvous and docking nor developed for service actions such as repair or refueling. In case of debris removal missions, the targets are often uncontrolled and can even be damaged and tumbling. This is why OOS missions highly differ from formation flying or rendezvous and docking to the space station.

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At DLR space operations, the scientists focus on safe and robust rendezvous to non-cooperative, passive and potentially tumbling targets. With the EPOS facility (see RB Portfolio EPOS), the motion of such targets can be simulated and the rendezvous phases can be tested within hardware-in-the-loop simulations. This is used for testing DLR's guidance, navigation and control (GNC) system for rendezvous which is an on-board software system for rendezvous. DLR-German Space Operations Center (GSOC) provides know-how and on-board software and technologies especially for the rendezvous phase.

DLR space operations also provide operations of on-orbit servicing missions. These missions require on the one hand standard multi-mission operational tools, for example for telemetry monitoring and telecommand generation, but also some specific features which are specifically developed for servicing missions, for example the support of telepresence. GNC system development, hardware-in-the-loop simulation and the ground segment for OOS missions are integrated in a unique end-to-end simulation environment at DLR.

Highlights

- Relative Guidance, Navigation and Control
- On-Board Computing
- End-to-End Simulation

Read More

- RB Portfolio: **European Proximity Operations Simulator (EPOS)**
- Benninghoff et. al. (2018) End-to-end simulation and verification of GNC and robotic systems considering both space segment and ground segment. CEAS Space Journal

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Photos

2. Relative Guidance, Navigation and Control for Rendezvous

The rendezvous Guidance, Navigation and Control (GNC) system controls the approach to a non-cooperative target object by a chaser satellite. The approach is based on optical sensors in a controlled, safe and partly autonomous way. At the final hold point, called mating point, the final, desired relative position and orientation between chaser satellite and target satellite is reached such that the client can be captured.

We provide expertise (know-how, consulting) and technology (such as on-board software and simulation hardware & software) and we focus mainly on the close range rendezvous phase.

The single components of the GNC system are described in the following sections.

2.1 Navigation

The navigation component is the core and most challenging part of the GNC system for rendezvous. The task is to provide an estimation of the target's state (e.g. position, velocity, attitude and attitude rate) based on the information of rendezvous sensors. The state estimation has to be continuous, accurate and smooth.

2.2 Navigation Sensors and Pose Estimation

2.2.1 2D Camera

A 2D camera is often the primary rendezvous sensor since it has typically low mass and low power consumption compared to other sensors and is easy to integrate on-board of a service satellite. A number of public and free image processing algorithms and libraries exist. However, camera based navigation for OOS is still not a completely solved and easy task. For autonomous navigation on-board a satellite, the main challenge is the computational effort of image processing algorithms dealing with on-board computers with significant less performance and memory than standard terrestrial workstations. The main task is the selection of appropriate algorithms, adaptations and integration to on-board computers and necessary application dependent tuning and optimization. Also lightning conditions (direction of the Sun, eclipses, shadows) have to be taken into account when developing a robust and safe camera based navigation system. The use of a mono 2D camera requires a model of the target such that the 6D pose (position and orientation) can be measured from camera images. Sometimes, an accurate model has to be first generated during an inspection phase. The camera system has to be chosen carefully. The accuracy of camera based pose estimation mainly depends on the field of view of the camera optics and the resolution of the camera chip. Often a system of far range and close range cameras with at least two different fields of view is selected.

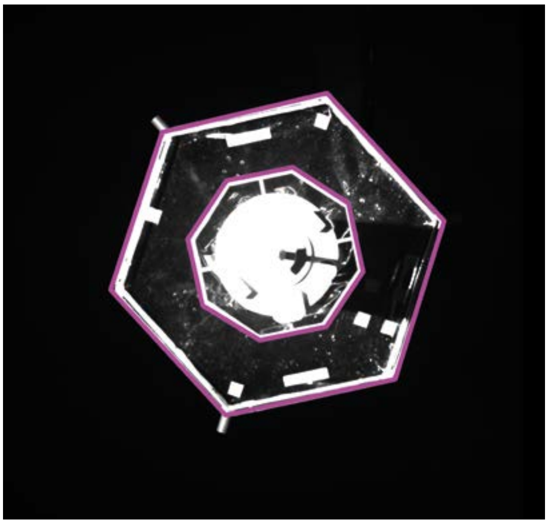


Fig. 2-1 Exemplary image of a mono camera taken at the DLR's EPOS 2.0 facility and the result of the pose estimation (visualised by model edges projected back to the image).

2.2.2 Scanning LiDAR (Light Detection And Ranging)

A LiDAR is typically used as rendezvous sensor. Its main advantage is that it has very accurate distance measurements. Based on the principle of the time of flight, the LiDAR delivers for each scanning point a measured distance. With little computational effort compared to camera based image processing, a rough position estimation can be calculated from a 3D point cloud. A LiDAR can thus support a camera sensor.
It can be used as backup sensor, as sensor for retreat maneuvers in case of failures of the camera, as mid range sensor but also as close range sensor as primary sensor or in sensor fusion with cameras. Also the full 6D pose can be measured using LiDAR data in principle.

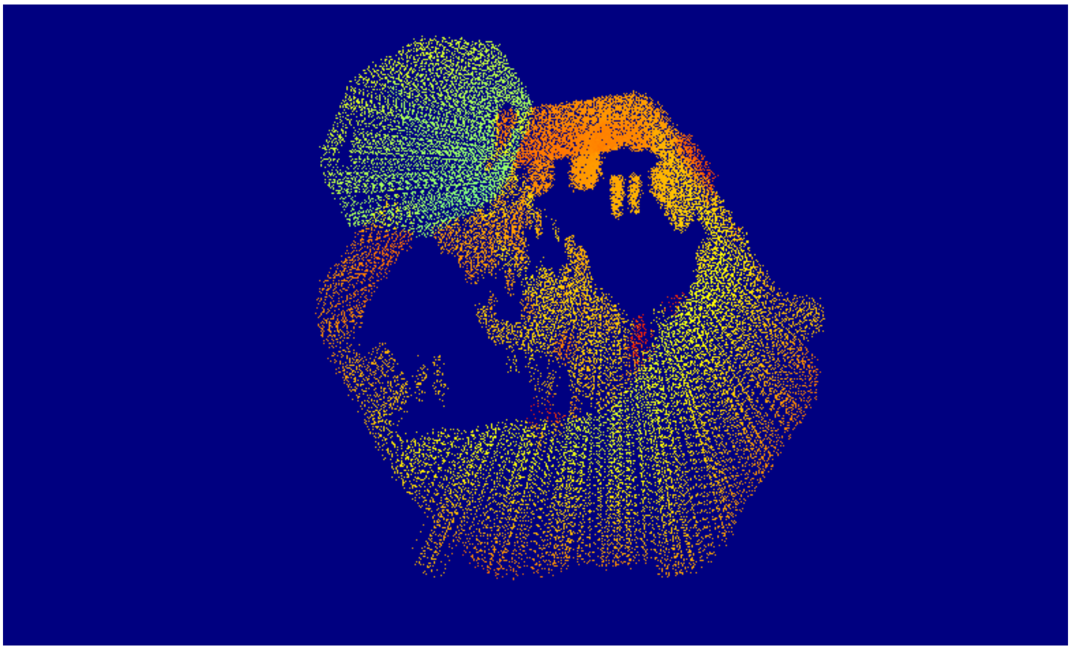


Fig. 2-2 Example of a LiDAR point cloud generated at the EPOS 2.0 facility.

2.2.3 Other sensors

A variety of rendezvous sensors can be used such as radar sensors, stereo or thermal/infrared cameras and Flash LiDARs. At DLR, we also gained experience with a new type of sensor: photonic mixed device (PMD) cameras. A PMD sensor is an active matrix sensor that computes the distance for each pixel based on the phase shift between sent signal and received signal. However, no space qualified PMD sensor exists yet, but it is an interesting sensor for research and use in laboratories.

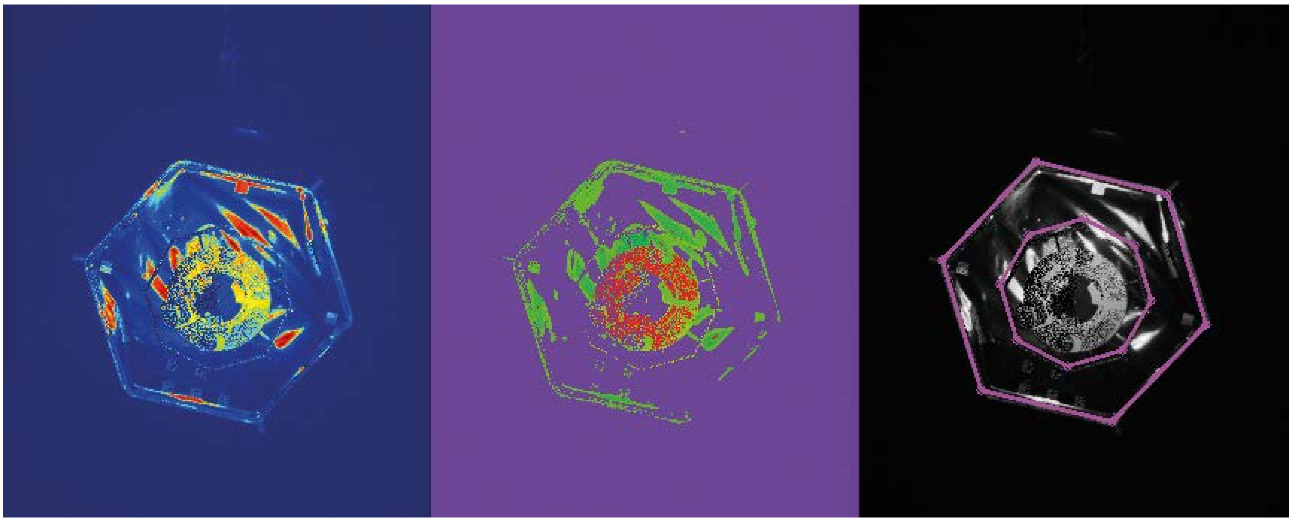


Fig. 2-3 Exemplary image of a PMD camera taken at the EPOS 2.0 facility. Left: PMD amplitude image, center: PMD depth image, right: result of the pose estimation (visualised by model edges projected back to the image).

2.3 Navigation Filter

DLR provides a navigation filter specially developed for rendezvous. It is based on an Extended Kalman filter and provides an estimation of the target's state in Earth Centered Inertial (ECI) coordinates. The filter can deal with asynchronous measurements, which means that the measurements need not be provided to the filter with a constant frequency and need not be time-synchronized with the filter update times. The measurement can also be delayed, as expected for real missions: After the capturing of camera images, for example, image processing routines find the visual features of the target in the image and the relative pose is computed. Image processing is often time-consuming, especially with on-board computers. This is why a navigation filter has to cope with delayed measurements.

The filter further has different inputs and can use measurements from different sensor sources, for example from mono camera, PMD camera and/or LiDAR. By tele-command the sensors which should be used for the navigation can be selected. If more than one sensor is selected, the filter automatically performs sensor fusion. The different sensors need not to be synchronized. If two sensor measurements are accepted, there can be time steps when two sensors are used, time steps when only one sensor delivers a new measurement and time steps when no new measurement is available. Typically, the filter is executed with a much higher frequency than the sensor processing systems. By propagation of the orbit and attitude of the target based on dynamic equations, the filter can generate smooth state estimates also in time steps where no sensor measurement is available.

2.4 Guidance

The guidance component of the GNC system provides a guidance trajectory which consists of desired position, velocity, acceleration and orientation in the Local Vertical Local Horizontal System (LVLH) for the chaser during the approach. The guidance trajectory consists of several sub-trajectories which parameters can be commanded from ground. The sub-trajectories are executed on-board in an autonomous way and stop automatically at a hold point. The guidance component is implemented as a state machine. The state can be changed via telecommands, such as “start straight line approach to d=15m with v=0.02m/s”.

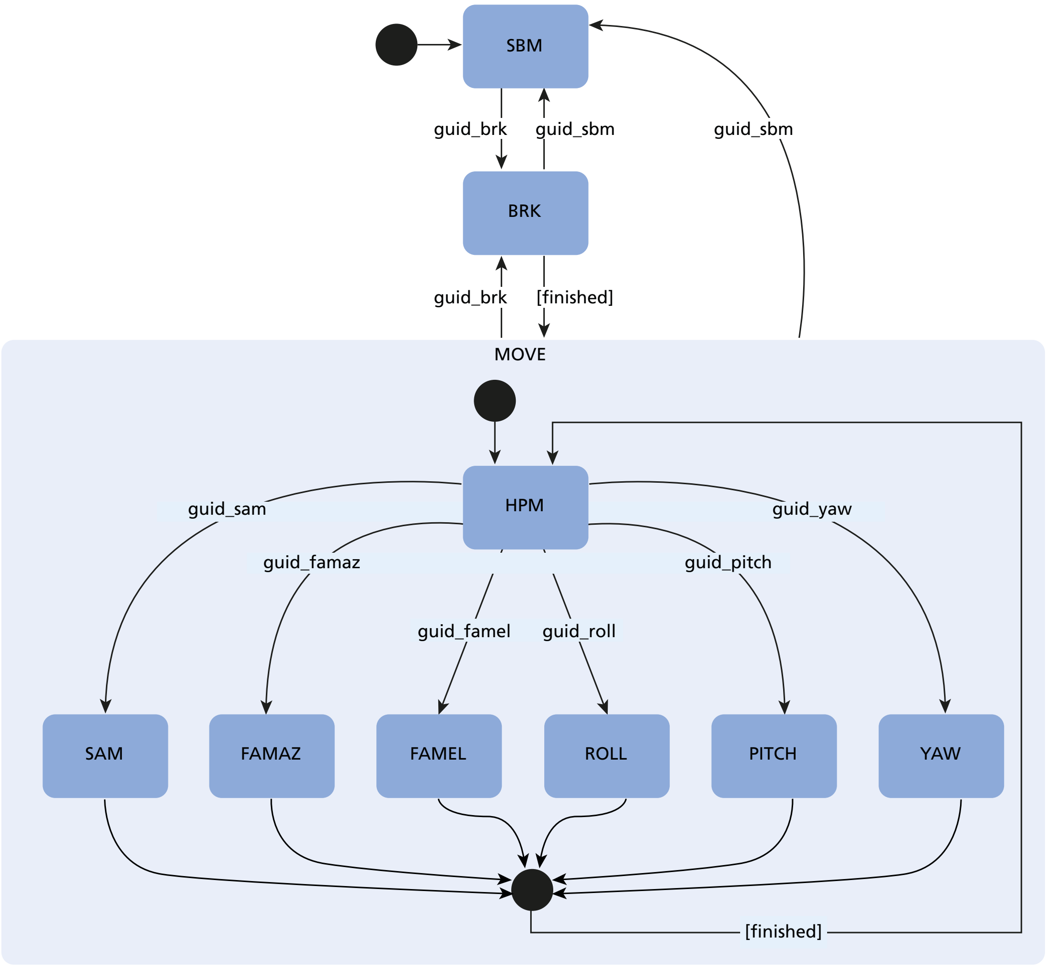


Fig. 2-4 Diagram of the guidance state machine. SBM = stand-by mode, BRK: break mode, HPM = hold position mode, SAM = straight line approach mode, FAMAZ = fly around azimuth mode, FAMEL = fly around elevation mode, ROLL = roll motion mode, PITCH = pitch motion mode, YAW = yaw motion mode.

2.5 Control

The control system completes the GNC system. Its basis is an LQR (linear quadratic regulator) with a leading integrator term. It is equipped with a feed forward control which models the dynamic position of the chaser according to the Clohessy-Wiltshire equations (= a set of dynamical equations describing the orbit dynamics for rendezvous).

2.6 On-Board Telecommand and Telemetry Handling

The GNC system is designed for an autonomous execution on-board the chaser satellite during an on-orbit servicing mission. The operator on-ground mainly monitors the telemetry and sends tele-commands to its GNC payload. By tele-command, parameters or states of the subsystems can be changed (see navigation filter or guidance description above).

Telemetry multiplexer and telecommand demultiplexer are implemented for the GNC on-board system, following the associated CCSDS/ECSS standards. Each component generates complete telemetry packets, receives telecommand packets and executes the corresponding commands.

2.7 Implementation

The rendezvous GNC system’s implementation is in line with the “new space” philosophy. In many ways, it goes beyond traditional software development for spaceflight.

Instead of relying on decade old compilers and programming language standards, the rendezvous GNC system is implemented in modern C++14 using state of the art compiler technology. The C++ standard of the software is continuously increased as new language versions are published and become well established. Modern compiler technology leads to faster software execution and shorter development iterations. Modern C++ allows writing less code with fewer bugs by catching many potentially severe problems at compile-time, that traditionally would have been caught only at runtime. Thus, modern software technology increases the rendezvous GNC system’s safety compared to traditional approaches.

The rendezvous GNC system’s implementation is backed up by a suite of automated tests that is continuously extended, and confirms by a single command that any of the frequent, iterative enhancements of the system don’t introduce new bugs.

The architecture is at its heart parallel. High performance on-board computing will only be possible by heavy parallelisation, as has been foreshadowed by terrestrial computing technology during the last two decades. This parallel architecture serves as an enabler for computationally expensive sensor data processing and sensor fusion in the rendezvous GNC system.

The rendezvous GNC system targets the real-time linux operating system, on desktop for convenient testing as well as on embedded for realistic conditions. Real-time linux has become widespread in the last years in terrestrial applications, especially in robotics. It combines a hard real-time operating system with the linux ecosystem of tools and libraries, and thereby safety-critical determinism with the possibility of rapid and convenient development.

2.8 On-Board Computing

A challenging task for autonomous rendezvous is the lack of performance of classical on-board-computers, especially for computation-intensive but vital tasks like image processing.

This problem is tackled from two sides: On the one hand, more efficient algorithms with less need for computing-power and memory have to be applied. On the other hand more powerful but still space-capable hardware is needed.

A promising solution makes use of current trends applying commercial-off-the-shelf hardware. A flexibly configurable arm-processor-based multi-node-approach both increases reliabilty through redundancy, and makes use of parallelisation for increased performance. Regular experiments on EPOS demonstrate the feasibility of such an approach: A stable mono-camera based close-range-approach is possible with a two-node ARMv5 configuration.

3. End-to-End Simulation

The GNC system for rendezvous is part of an end-to-end simulation framework developed in cooperation with four institutes of DLR (space operations and astronaut training, institute of robotics and mechatronics, institute of system dynamics and control, institute of optical sensor systems). An end-to-end test and simulation environment is established by a simulated space segment for on-orbit servicing and a real ground segment connected with a communication system and a simulation of the communication path between space and ground.

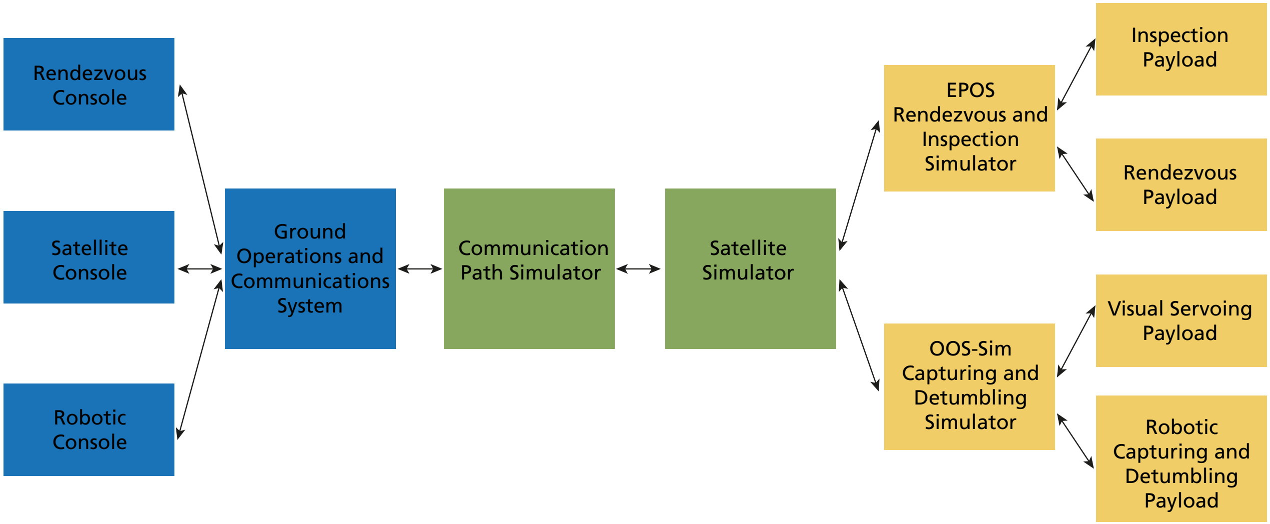


Fig. 3-1 The different components of the end-to-end simulation framework (blue: ground segment, green: software simulation, yellow: hardware-in-the-loop simulation with payloads)

The end-to-end simulation is developed within a project called RICADOS (Rendezvous, Inspection, CApturing and Detumbling by Orbit Servicing). The system can be used both for research but also by customers or cooperation partners for dedicated end-to-end test campaigns (see RB Portfolio EPOS).

3.1 Communication

The communication system interconnects all subsystems of the end-to-end simulation. It provides real-time communication capability allowing to send and receive timely deterministic data packets for example for the robotic payload. It allows parallel operations of the housekeeping (satellite bus) operation and real-time robotic telepresence. For this purpose, a merger is developed and integrated. It is a device based on custom programmed field programmable gate array (FPGA) with a stringent timing. It can receive two command streams with CLTUs (communications link transmission units) from two sources, use buffers to accommodate for potential delays and send the CLTUs out at a timed fashion to the service satellite / the service satellite simulator.

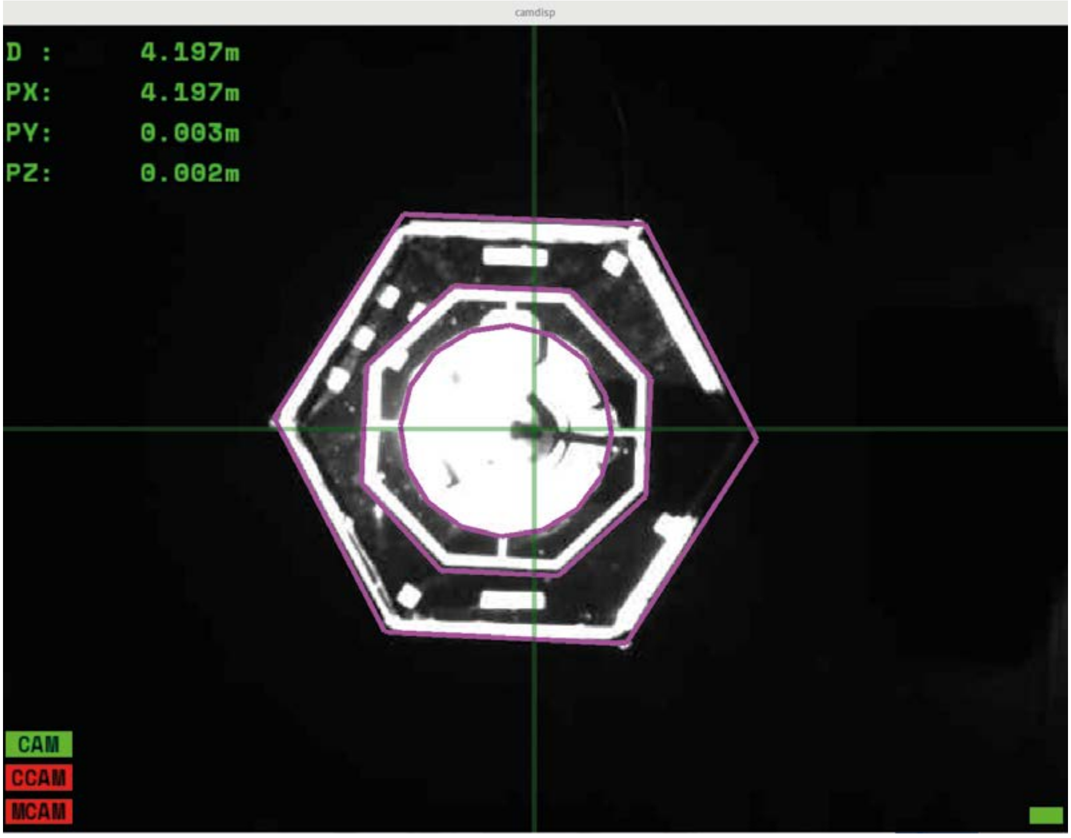
Another FPGA-based device, the IP firewall has been developed. It decapsulates spacecraft data (CLTU or telemetry frames) out of UDP/IP datagrams, moves it within internal registers and packs it into new UDP/IP packets. This is done on a stringent time base, not to induce any jitter or delays.

A wide area network (WAN) simulator is integrated between merger and IP firewall to simulate the communication path between ground segment and space segment. It is a software system which allows changes in the package delay and induces jitter or packet loss on purpose. This is used to simulate longer space links (like over GEO relays) in a deterministic manner. This is an important feature for realistic simulation and test of robotic telepresence tasks (for capture or maintenance activities within OOS missions).

3.2 Operations

The on-orbit servicing developments are integrated within GSOC's control center. Many flight-proven tools for mission operations, configuration items, procedures and infrastructure present at GSOC are used for simulation and training of on-orbit servicing missions and can be used with only some minor mission specific adaptations for real future servicing or debris removal missions.

Three console types exist: the satellite operations console, the rendezvous console and the robotic console. They all contain the GSOC mission control system called GECCOS (based on SCOS-2000), GSOC's standard display system called SATMON and many other mission operations tools. They provide access to the operational web and fileserver, where all mission relevant information is gathered (flight procedures etc.). Additionally, specific tools for rendezvous, inspection or robotics are integrated on a dedicated virtualised host. Examples for such specific tools are visualisations and images of rendezvous sensors during contact phases of the ground with the simulated service spacecraft.



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D :     4.197m
PX:     4.197m
PY:     0.003m
PZ:     0.002m
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Fig. 3-2 Camera display at the rendezvous console showing a compressed live-image of the rendezvous camera during contact with the satellite. The result of the pose estimation is read from the telemetry and an overlay is printed. Further the distance and the position measurement are shown. At the bottom left corner it can be selected between standard camera (CAM), close range camera (CCAM) and mid range camera (MCAM).

3.1 Satellite Simulator

The satellite simulator is the central part of the end-to-end simulation. It is connected via the communication system with the ground segment and is connected with the on-orbit servicing payloads (inspection payload, rendezvous payload, robotic payload) via the hardware-in-the-loop test facilities EPOS (European Proximity Operations Simulator, see **RB Portfolio EPOS**) and OOS-Sim (On-Orbit Servicing Simulator for Capture), both located at DLR Oberpfaffenhofen.

The satellite simulator contains simulation specific components such as the physical orbital system with a simulation of orbit and attitude dynamics in real-time. In a mission, the simulation specific components are replaced by the real systems, i.e. by the satellites and their environment. The satellite simulator also contains mission specific components that would also exist in a real-mission like the on-board telemetry and telecommand handling system or frontend processes like power subsystem frontend, AOCS (attitude and orbit control system) frontend with an ECSS PUS (packet utilization standard) compatible interface.

3.2 Hardware-in-the-Loop Simulators and Payloads

The satellite simulator is connected to EPOS, the facility used for inspection and rendezvous, and provides motion commands for the facility. A software called ExtEPOS (External EPOS Interface, see also **RB Portfolio EPOS**) computes commandable positions and attitudes for the robots of the facility.
The rendezvous sensors (see Section "Relative Guidance, Navigation and Control for Rendezvous") are mounted at one robot of the facility simulating the chaser. A target mockup (like the mockup of a client satellite or of a debris object) is mounted at the second robot of the EPOS facility. The data of the rendezvous sensors are processed by the GNC payload computer. The output of the controller is sent to the satellite simulator, to the simulation of the actuator system. Thus, closed loop simulations are realized. The payload can also receive telecommands and telemetry as described above. This completes the end-to-end simulation.

After a successful rendezvous, a handover is done to the robotic system for capture. The capturing can be performed for example by a robotic arm like in our regular scenario. The capturing is simulated with the OOS-Sim located at DLR's robotics and mechatronics center. Similarly to the rendezvous payload, the robotic payload is connected via the satellite simulator to the end-to-end system. Both autonomous capture and telepresence can be performed.