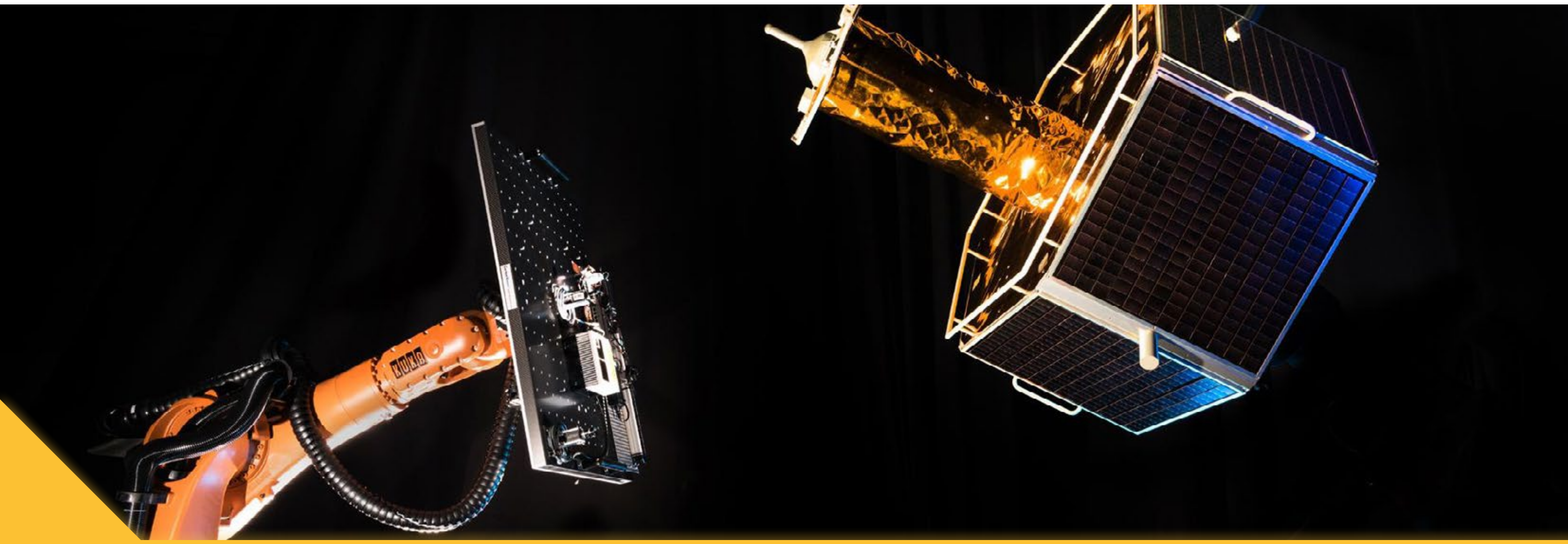
European Proximity Operations Simulator



European Proximity Operations Simulator

Test and verification play major roles in the preparation of space missions. Especially classes of missions like robotic servicing missions, debris removal missions, sample return missions and other close proximity missions require intensive tests of the involved systems and sub-systems.

The European Proximity Operations Simulator (EPOS) 2.0 is a robotic test facility, developed in 2008/2009. Its predecessor, EPOS 1.0, built in the 1980s, was a joint test facility of DLR and ESA. Rendezvous and docking systems mainly for cooperative rendezvous, such as sensors of ATV (Automated Transfer Vehicle), for rendezvous to the ISS, have been tested and validated with EPOS 1.0.

EPOS 2.0 is a large-scaled test facility. The simulated orbital relative navigation can be used with a variety of optical sensors and target bodies and is integrated into DLR's end-to-end test infrastructure. By that EPOS 2.0 is able to support test and validation of sensors (open loop), optical guidance, navigation and control systems (closed loop) or on-orbit servicing and related missions (end-to-end).

Test Facility

- Robotic test bed with two KUKA robots
- Large scale facility (25m rail system)
- Hardware-in-the-loop simulations (sensor- / processor-in-the-loop)
- Real-time simulation
- Sun simulation
- Realistic background
- End-to-end test capability

Read More

- RB Portfolio: **On-Orbit Servicing Technologies**
- EPOS @ Journal of Large Scale Research Facilities
- EPOS @ DLR Großforschungsanlagen
- EPOS @ Mess Tec Database
- Rems, Florian, Frei, Heike, Risse, Eicke-Alexander, Burri, Matthias (2021): 10-Year Anniversary of the European Proximity Operations Simulator 2.0 - Looking Back at Test Campaigns, Rendezvous Research and Facility Improvements. Aerospace, 8 (9), Multidisciplinary Digital Publishing Institute (MDPI). doi: 10.3390/aerospace8090235.

Location

The European Proximity Operations Simulator (EPOS) is part of the German Space Operations Center at the DLR Oberpfaffenhofen.

Point of Contact

German Aerospace Center (DLR)
Space Operations and Astronaut Training
Dr. Heike Frei | Florian Rems
Muenchener Str. 20, 82234 Wessling

E-Mail: Heike.Frei@dlr.de
Florian.Rems@dlr.de

DLR.de/RB

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Münchener Straße 20, 82234 Weßling

2. Facility Elements

2.1 Robotic based hardware-in-the-loop simulator

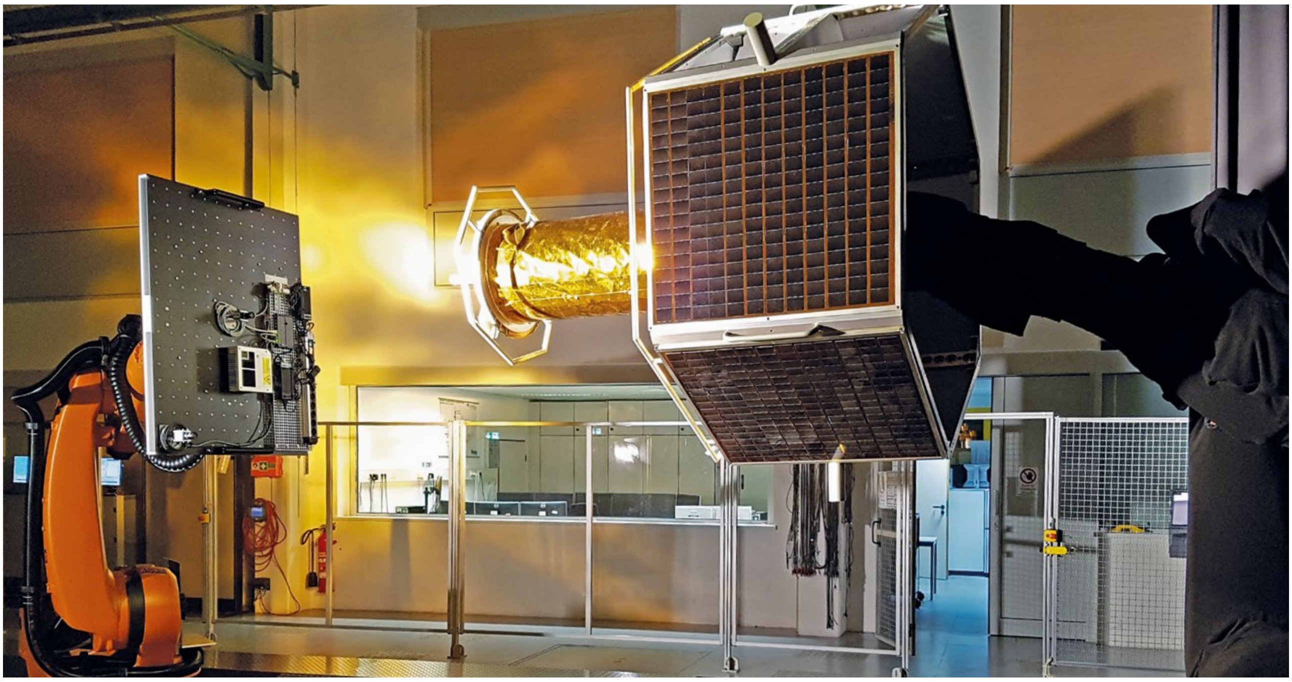


Fig. 2-1 The European Proximity Operations Simulator (EPOS) 2.0 - Facility for testing autonomous guidance, navigation and control systems for rendezvous and inspection missions

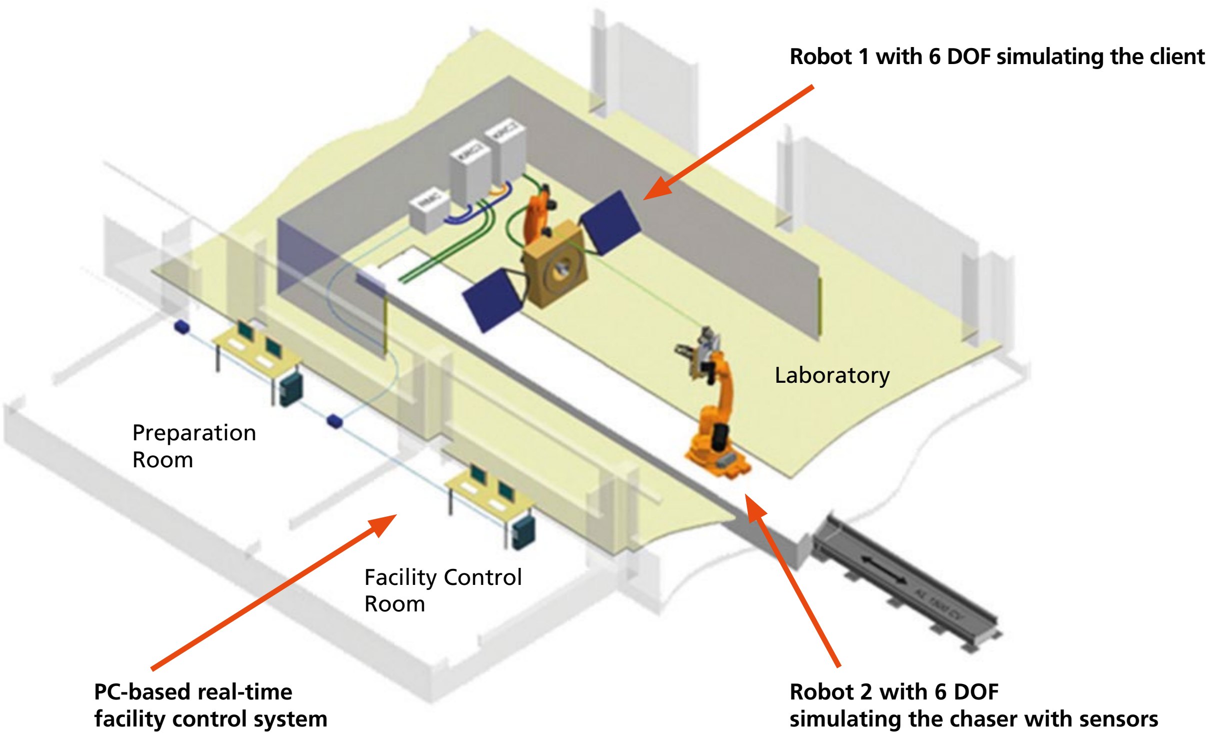


Fig. 2-2 Layout of the EPOS facility with two robots, one simulating the chaser, the second simulating the target

The EPOS facility is a robotic based hardware-in-the-loop test facility for simulation of rendezvous and inspection phases of close proximity or robotic missions. Its main elements are:

- A rail system KUKA KL1500 on the laboratory floor to move an industrial robot up to a distance of 25m,
- A KUKA KR100 HA (HA = High Accuracy) robot mounted on the rail system simulating the 6 degrees-of-freedom (DoF) motion of one spacecraft / one object,
- A KUKA KR240-2 robot mounted at one end of the rail system for simulation of the 6 DoF-motion of a second spacecraft / object.

The KUKA KR240-2 can be configured with an endless axis 4 and/or endless axis 6.
Endless-turning motions can be thus realized.

Robots and rail are surrounded by a protective fence.

The technical data of the rail and the robots is summarized in the following tables.

Parameter	**KUKA KL 1500 (rail)**
Type	Linear axis with rack-and-pinion drive
Payload mass maximum	3000 kg
Rail mass (without robot)	ca. 13500 kg
Repeatability	+/- 0.02 mm (ISO 9283)

Table 2-1 Technical data of the rail

Parameter	**KUKA KR100-HA (robot 1)**	**KUKA KR240-2 (robot 2)**
Type	6-axis articulated robot	6-axis articulated robot
Payload mass maximum	100 kg	240 kg
Robot mass (without control part)	1200 kg	2700 kg
Repeatability	+/- 0.12mm (ISO 9283)	+/- 0.12mm (ISO 9283)
Mounting	Rail	Floor

Table 2-2 Technical data of the robots

The maximum payload mass is a theoretical upper limit for an ideal mass with small moments of inertia.
In practice, payload data (i.e. the entire system including parameters like mass, moments of inertia, dimensions and sizes) has to be analyzed in detail before it can be mounted on one of the robots.

EPOS is a large-scaled robotic test facility for simulation and test of proximity operations up to 25 m distance.

2.2 Sun Simulator

For space-representative illumination conditions, a prerequisite for tests of optical sensors, an ARRI Max 12/18 spotlight is available at the EPOS facility. The spotlight is equipped with a 12 kW Osram HMI (hydrargirum medium-arc iodide) lamp with a high luminous flux and a daylight color-temperature of 6000K.
Color rendering index is 90.

Fig. 2-3 ARRI MAX 12/18 used as Sun simulator at the EPOS facility

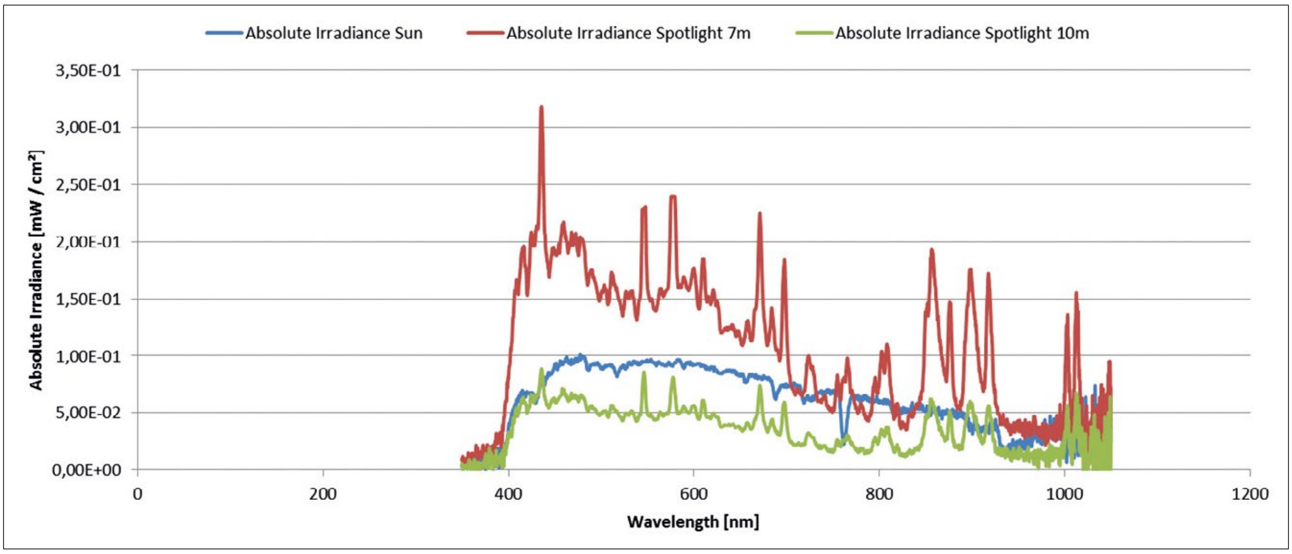


Fig. 2-4 The absolute irradiance of the sun simulator at 7m and 10m distance compared with the Sun light in an Earth orbit

A distance between 7m and 10m between spot light and object has to be chosen for Sun simulation, dependent on the spectral sensitivity of the used sensor.

Realistic simulation of illumination conditions is the basis for test and verification of optical sensors.

2.3 Background

The background of robot 2 is covered with a black Molton curtain and carpet. Also the robotic arm of robot 2 is wrapped in Molton, such that nearly no objects in the background or the robot itself are visible in data of visual cameras.

Fig. 2-5 Possible setup for sensor tests with pure black background: EPOS robot 2 (left) wrapped in black Molton with a mockup of a satellite and with Molton curtain in the background and EPOS robot 1 (right) with sensors on its adapter plate.

2.4 Commercial-Off-the-Shelf (COTS) Rendezvous Sensors

One possible usage of EPOS is test and verification of rendezvous and inspection sensors. Sensors of customers or cooperation partners can be mounted at the adapter plate of one of the two EPOS robots. DLR-RB does not develop sensor hardware on its own. However some commercial-off-the-shelf sensors exist which can be used as well. This can be useful when first algorithm tests (for example image processing algorithms) or proof-of-concept tests should be done where no space-representative sensors are needed.

The sensors available at EPOS are summarized by the following table:

Sensor Name	**Sensor Category**	**Parameters**	
Prosilica GC655	2D mono camera, CCD, 2 cameras available	Resolution: 480 x 640 pixels, Field of View: 41 x 53 degrees	
Prosilica GT2050	2D mono camera, CMOS, 2 cameras available	Resolution: 2048 x 2048 pixels, Field of View: 18 x 18 degrees (mid-range camera) and 47 x 47 degrees (close-range camera)	
DLR-Argos 3D-P320	Photonic Mixed Device camera	Resolution: 352 x 287 pixels, Field of View: 29 x 24 degrees	
Livox Mid-40	Scanning LiDAR	Circular field of view: 38.4 degrees	

Table 2-3 COTS-sensors available at EPOS

2.5 PC-Based Simulation and Control System

The EPOS facility is controlled by a computer-based system with several hierarchical levels.

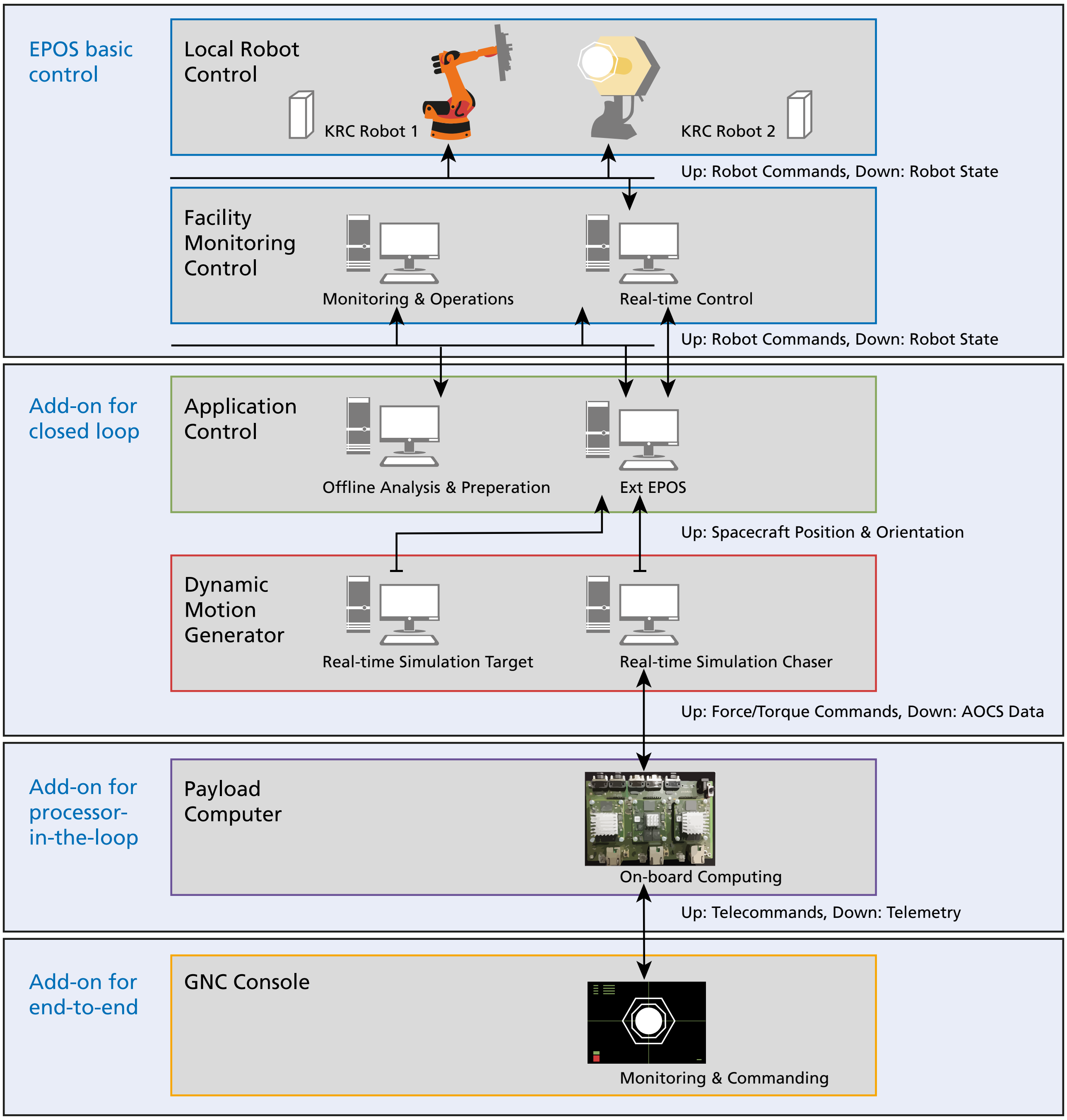


Fig. 2-6 The EPOS control levels and their interactions

2.5.1 Local Robot Control System

The local robot control system is responsible for controlling the axes of the robots. Each robot is independently controlled in real-time by its own local robot control unit, provided by the robot manufacturer (KUKA robot control KRC2). Both KRC2 cabinets in the EPOS facility can be externally commanded with a command rate of 250 Hz and are synchronized to the EPOS external time base.

2.5.2 Facility Monitoring and Control System

The facility monitoring and control system controls and monitors the entire facility in real-time including monitoring and logging of all parameters and states of the facility. One can choose among different control interfaces: The main command interfaces are: synchronous command interface (EtherCAT) for closed loop applications and asynchronous command interface for open loop applications (run a predefined trajectory stored in a file).

2.5.3 Application Control System

The application Control System is used for simulations where the actual trajectory for the robots is not pre-defined but computed in real-time. On this level, a software called ExtEPOS (External EPOS Interface) runs. ExtEPOS receives position and orientation values for the two moving objects of the application and transforms these values to commands for the robots in the laboratory. The transformation from any application dependent coordinate system (like Earth Centered Inertial frame) to the laboratory coordinate system is computed in a collision-free and safe way. ExtEPOS is implemented in a Matlab/Simulink Environment. The Embedded Coder is used for automatic code generation for a VxWorks operating system where the final real-time application is executed.

2.5.4 Dynamic Motion Generator

The dynamic motion generator is a system which computes the actual simulation. It can consist of a satellite simulator involving two satellites and their dynamic behavior, for example. A satellite simulator for two satellites in an Earth orbit exists at EPOS and is available. The dynamic motion generator can be replaced by a system of a customer or cooperation partner. Using ExtEPOS (see Application Control System) EPOS is able to synchronize its robots to external simulators.

2.5.5 Payload Computer

The payload computer simulates or represents the on-board computer where all processing steps of the payload are executed. In addition to sensor tests, also on-board algorithms and their performance can be tested with EPOS. The payload computer receives the sensor data of the sensors mounted on one of the EPOS robots and computes inputs to the dynamic motion generator (like force / torque commands for example).
The payload computer can be a work station or an embedded system. Such payload computers exist at EPOS but can also be replaced by a computer of the customer or cooperation partner.

2.5.6 GNC Console

The GNC console is part of GSOC control center and located in a control room next to the EPOS laboratory. At GSOC, it is possible to perform end-to-end simulations with simulated space segment and communication, and a ground segment as for a real mission. Tele-commands can be sent to the payload computer from the console and telemetry of the payload can be monitored during simulated passes with the spacecraft.

Simulations and tests can be done with all or with only a sub-set of these components:
For open loop tests only the local robot control and the facility monitoring and control system is needed.
For closed loop tests without using any tele-commands the GNC console is not needed.

> With different control hierarchies and modular control options, EPOS can be used for open loop, closed loop and end-to-end tests.

2.6 EPOS Safety System

The robots are surrounded by a protective fence which has to be locked before an automatic external motion can be commanded to the robots. From the facility monitoring and control station all safety parameters like the status of the robots, the doors and the emergency stops can be monitored and checked. The KUKA Safe Robot Package is used for keeping a minimum distance of the movable parts, the robot with its payload, with respect to floor, walls and fences.
Laser Safety: It is possible to use also sensors or other hardware that actively emit light with harmful optical radiation. All doors and windows can be protected and a laser safety circuit can be activated. For this, lasers have to be connected to a 5V interlock signal provided at Robot 1.

> For each test campaign or project, a risk assessment is done and safety measures are implemented if necessary.

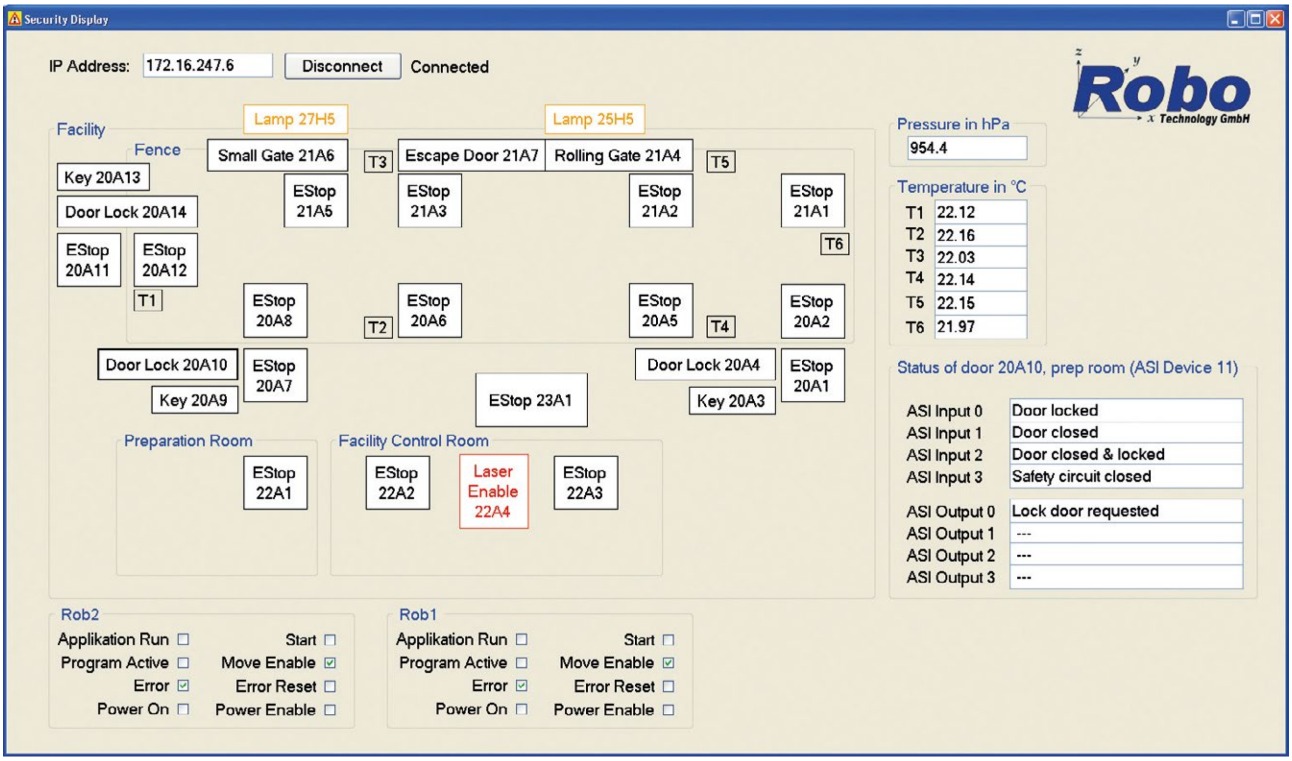


Fig. 2-7 Security display at the Facility Monitoring and Control System with Enabled Laser.

3. Interfaces

3.1 Mechanical Interfaces

The EPOS robots are equipped with an adapter plate where the user can mount test equipment.
The following table summarizes the parameters of the tooling adapter plates:

Parameter	KR 100 HA Tooling Adapter	KR 240-2 Tooling Adapter
Size	700 mm x 700 mm	1000 mm x 1000 mm
Maximum Payload	60 kg	200 kg
Pattern	Threaded hole pattern M6, 70 mm pitch	Threaded hole pattern M6, 70 mm pitch

Table 3-1 The KUKA KR 100 HA and KR240-2 Tooling Adapter Plate

3.2 Electrical and Data Interfaces

Each tooling adapter is equipped with an electrical interface block which allows the user to connect electrical test equipment (such as sensors like cameras, etc.) to a power supply and to transmit the data to the control room. The interface block is located at the backside of the adapter plate.
The available interfaces are:

- DC Power, 5 V, 4 A max, 3 terminals,
- DC Power, 12 V, 2 A max, 2 terminals,
- DC Power, 24 V, 2.5 A max, 3 terminals,
- DC Power, 28 V, 2.5 A max, 3 terminals,
- AC Power, 230 V, 50 Hz, 10 A max, CEE 7/4 socket,
- 2x data link terminal: female FCC RJ-48 (i.e. for Ethernet),
- HF data link terminal: female BNC / RG59.

Please note that the KR 240-2 robot, typically carrying a mockup of the target, has the ability to turn the target endlessly. If used, this capability comes with the restriction of having no electrical interfaces available at that robot.

3.3 Synchronization Interface

Either the GNC sensors on robot 1 or the control/processing equipment in the EPOS control room have to be connected with a GPS antenna cable. The GPS signal can be used to associate GPS time with sensor data capture time. The EPOS logfiles include the GPS time. Thus, the ground truth can be correlated with sensor data.

4. Rooms

In the following, an overview on the single rooms is given:

4.1 EPOS Laboratory

The laboratory comprises the robotic parts of the facility, where the robots, the rail system, the Sun simulator, the background curtain and the KUKA controllers are located.
The laboratory is divided in two parts: the robotic area surrounded by the protective fence (see EPOS Safety System) and the visitor area outside of the fence, where people can stay during simulations if no harmful light or laser is active.

4.2 EPOS Control Room

The EPOS control room is next to the EPOS laboratory. Via a window and via a camera based surveillance system the operator can monitor all actions inside the laboratory. The control room contains the work stations of the facility monitoring and control system, the application control system and – project-specific – the dynamic motion generator and payload computer. The payload computer can also be installed directly at the robot in the laboratory if desired.

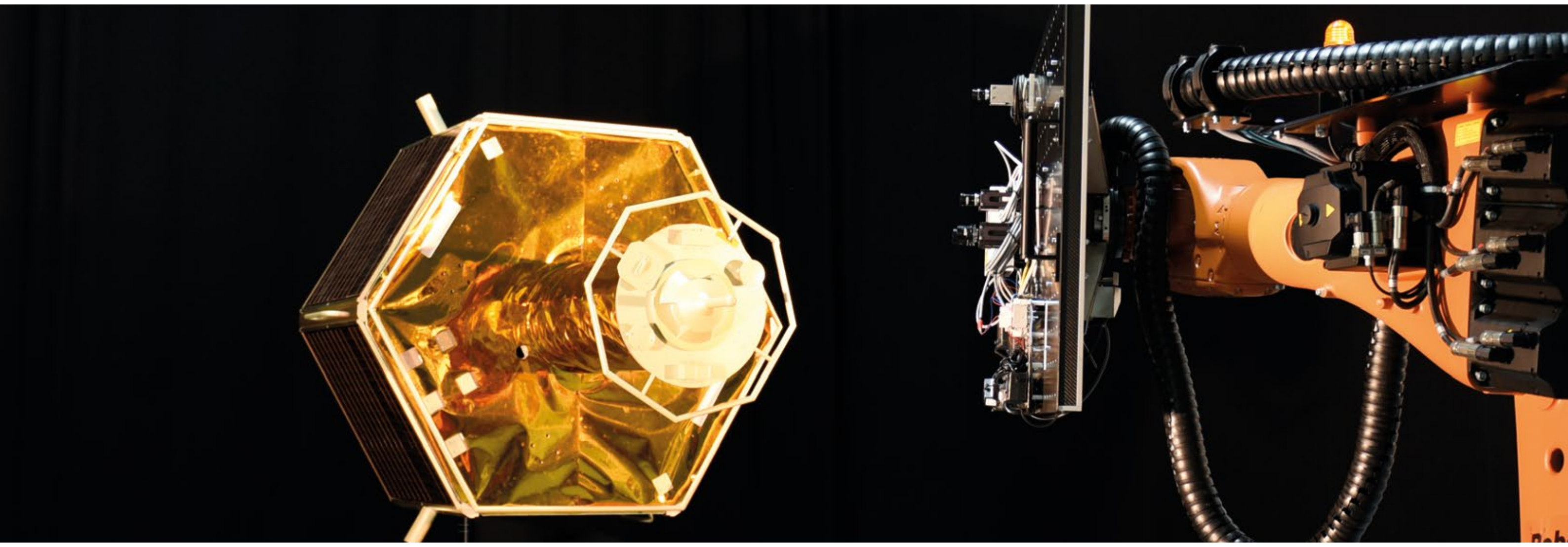
4.3 EPOS Preparation Room

The preparation room serves for all activities to prepare the tests. Both hardware and software preparations can be performed there.

4.4 Satellite Control Room

A satellite control room exists next to EPOS which can be used for end-to-end tests. From satellite consoles, tele-commands can be sent to the satellite and its payloads, if its on-board counterpart is implemented. Similarly, telemetry can be monitored and realistic operations can be tested and prepared. The space and ground interactions with simulated passes with the satellite can be trained.

5. European Proximity Operations Simulator (EPOS) Test Campaigns



The EPOS 2.0 facility serves for test, verification and validation and is used both by DLR for research purposes and by external customers and cooperation partners. The facility is a test platform for hardware test (with main focus on optical sensors) and software test (algorithms for sensor data processing, algorithm for guidance, navigation and control, etc.).

Sensors but also embedded systems like on-board computers with on-board software can be tested and verified. A unique feature of EPOS is that the facility is located in the German Space Operations Center (GSOC) with an end-to-end infrastructure that allows to connect the simulated space segment with a real ground segment. By that, the interaction between on-board payload and on-ground operations can be tested. This also serves as training platform for operators and as agile development framework for developers and scientists.
EPOS is mainly used for test of rendezvous and inspection sensors and systems. Applications are on-orbit servicing, debris removal, sample capture and return, cooperative rendezvous and formation-flying. But EPOS is not restricted to space applications. In principle, it can be used for all kind of proximity tests, for sensor-only tests, etc. Typically, the relative motion between two objects is of interest. This is realized by two industrial robots each with 6 degrees of freedom and one linear slide of 25m length on which one of the robots is mounted. Autonomous systems can be tested, but also man-machine interactions or telepresence.

Location
The test campaigns are executed at the European Proximity Operations Simulator (EPOS) 2.0 which is part of the German Space Operations Center at DLR Oberpfaffenhofen.

Target market

The EPOS facility can be used for test campaigns for example by
- Industry
- Academia
- Research institutes

Read More
- RB Portfolio: **On-Orbit Servicing Technologies**
- EPOS @ Journal of Large Scale Research Facilities

Features

- Test of sensors (camera, LiDAR, etc.)
- Test of embedded systems and on-board computers
- Test of GNC software
- Test of simulation software
- Integration of customer hardware and software
- Static and dynamic tests
- Different illumination conditions
- End-to-end tests

Test campaigns are planned, prepared and executed together with the EPOS-team of DLR space operations and astronaut training.

6. Test Categories

6.1 Open-Loop Tests

Definition
Trajectories for the EPOS robots are defined prior to the test. The test output, like sensor data, is logged during the test. Log files of EPOS (like the ground truth, position and orientation of the two robots with a frequency up to 250 Hz) are generated. The sensors can be connected with a GPS antenna and thus, the sensor data can be synchronized with the EPOS logging data. The trajectories are stored in simple text files and can be loaded and sent to the EPOS robots.

Advantages
Fixed trajectories allow repetition and comparison of tests. A typical test is the comparison of different sensor modes like different exposure times of a camera by using the same trajectory for each test. Another test is the comparison of different illumination conditions (with and without Sun simulation, different illumination angles, etc.).

Applications
Open loop tests are advantageous for comparing the performance of sensors or data processing algorithms when a trajectory should be repeated and different conditions should be compared and analyzed. At early development stages, software is sometimes not yet developed or not yet ready for tests under real-time conditions. With open loop tests, sensor data can be captured and stored for offline analysis and post-test processing.

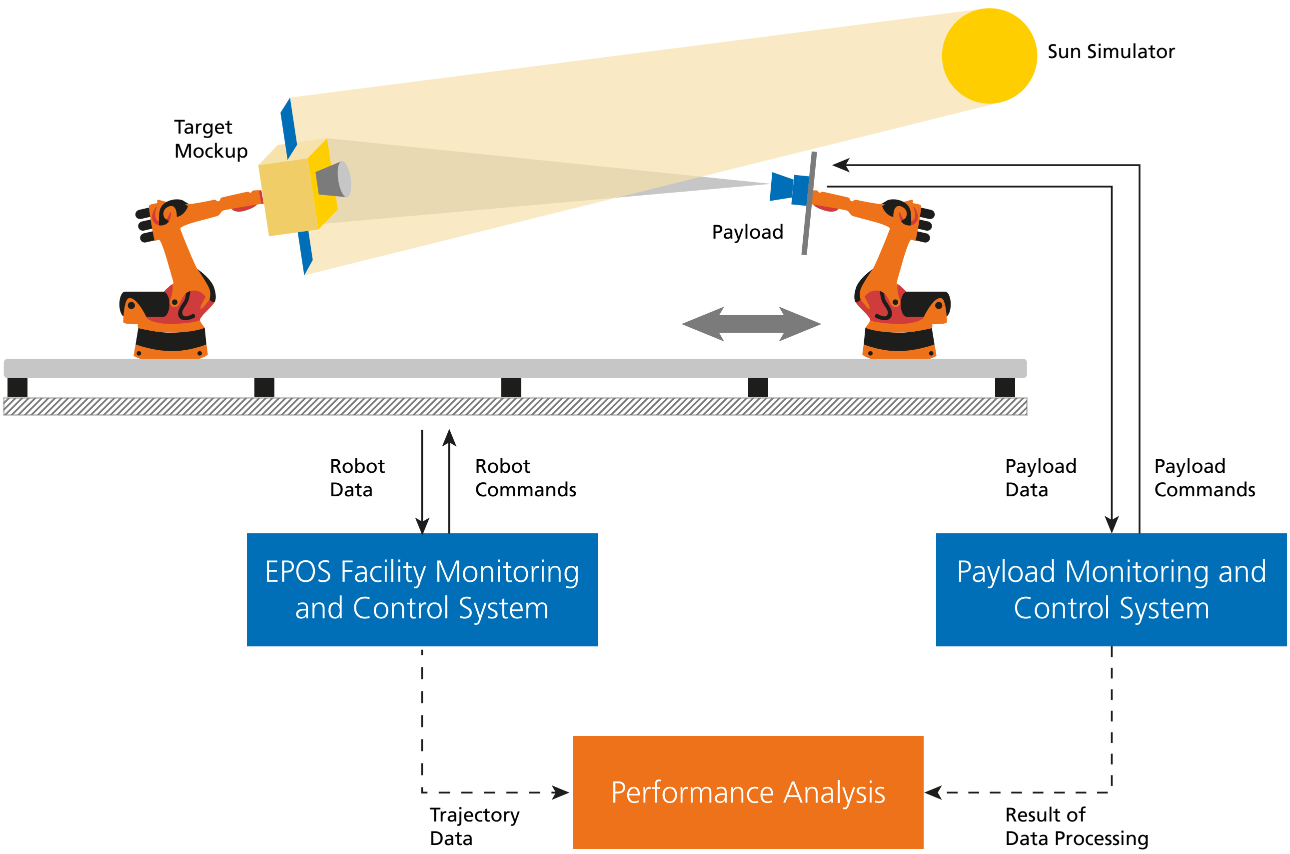


Fig. 6-1 The concept of open-loop tests

6.2 Manual Control Tests

Definition
A manual control unit is used and operated by a member of the DLR-EPOS team. Starting from any position and orientation of the robots, each robot joint or each Cartesian component can be changed manually. The values of the EPOS robots can be logged.

Advantages
A trajectory need not be defined in advance. The customer can express a desired position and/or orientation to the EPOS operator and the motion can be manually commanded.

Applications
This mode is often used for camera calibration. For such an application it is often hard to define a trajectory in advance. The different positions and orientations of the robot that carries the sensor can be iteratively changed by looking at the camera image and by performing corrections manually. This mode is used mainly when a final static position should be reached. It is not possible to move robot 1 and robot 2 at the same time.

6.3 Closed-Loop Tests

Definition
During hardware-in-the-loop tests, the input and output of the system to test is connected to its simulated counterpart: The motion of the two involved bodies is simulated in real-time and is generated by a software simulator. The sensor data is processed in real-time and the result, for example the measured relative position and orientation (=pose), is fed back to the control loop. Thus the sensor data and the result of the data processing influence the motion of the two bodies. The motion is not predefined.

Advantages
Sensor data is not only captured but processed in real-time. This allows testing not only sensor hardware but also full guidance, navigation and control software. By that, also the stability of control loops can be tested. Actual delays or simulated delays in control loops and the influence of outliers or measurement noise on the entire system can be investigated.

Applications
Closed-loop tests are necessary in preparation for a real-world usage of the system. The entire system (hardware + software and their interaction) can be tested in a simulated but very realistic test environment. Typical application examples are optical sensors in the loop (is the camera image processing and tracking accurate, robust and stable enough for a control loop?), processors in the loop (is the performance of the computing nodes good enough for a stable control loop?) or a combination of both.

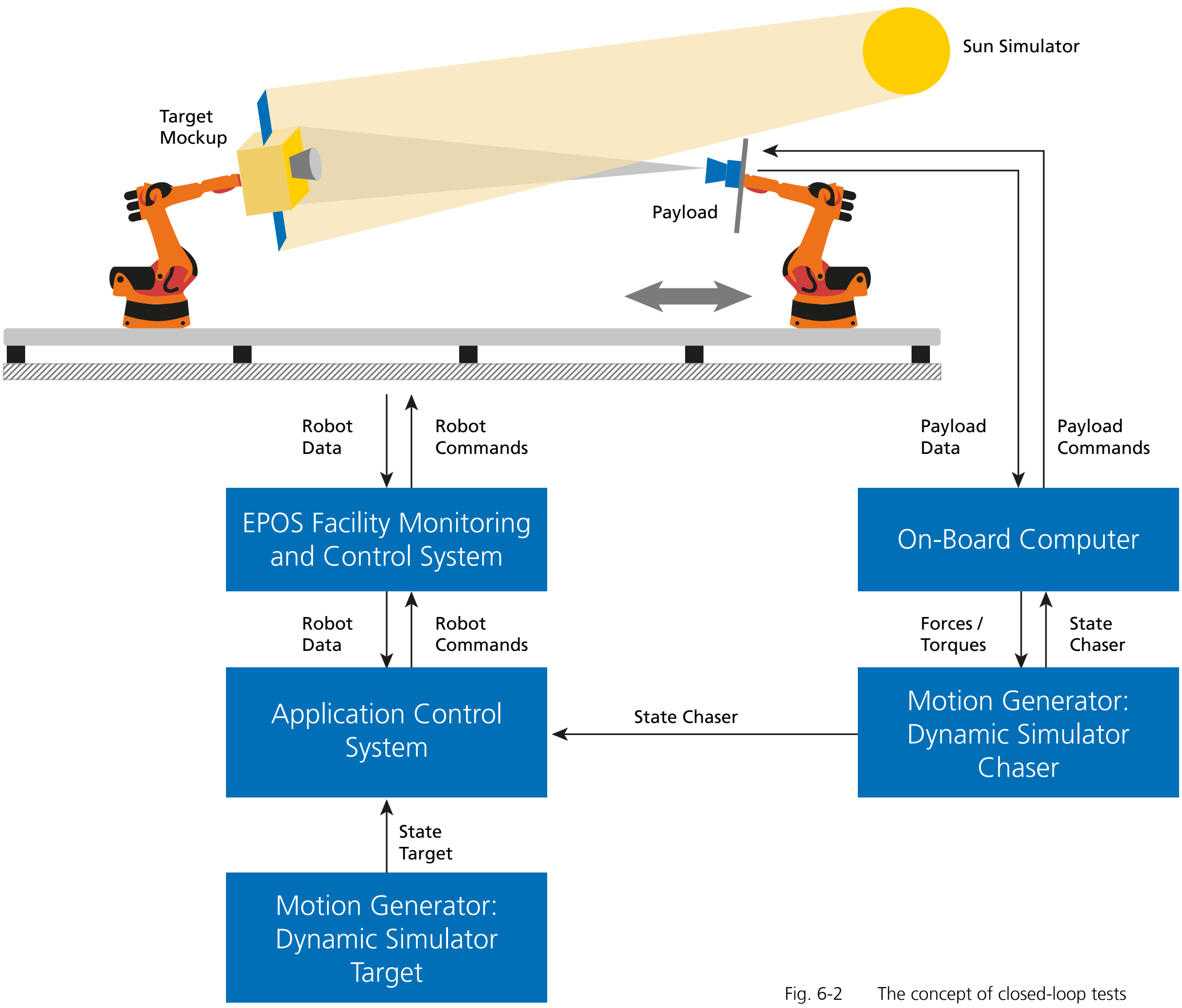


Fig. 6-2 The concept of closed-loop tests

6.4 End-to-End Tests

Definition

In the context of EPOS test campaigns, "end-to-end tests" are defined as the test of the complete chain of simulated space segment, simulated communication path and real ground segment. The basis is the close-loop test. The Motion Generator for Chaser is replaced by a satellite simulator which does not only perform dynamic simulation but also has an implemented on-board data handling and TM/TC (telemetry / telecommand) handling system. From a control room at GSOC at a console, the operators can send telecommands to their on-board system like activation of sensors, change of guidance modes and guidance parameters, etc.

Advantages

End-to-End tests provide all advantages of closed loop tests with the additional benefit of testing the entire communication chain between space segment and ground segment. Passes of the ground station with the chaser can be simulated. The setup is beneficial for testing the interactions of all systems and for operator training.

Applications

End-to-end tests allow integrating all main systems and subsystems and can be used during all development stages. It ensures that on-board system and on-ground system developments harmonize.
Thus end-to-end tests are important for continuous integration, agile development and to minimize the risk of failures (e.g. in the communication between space and ground). At DLR the simulator is connected also to a second robotic test-facility, the OOS-Sim located at the robotics and mechatronics center. A common satellite simulator for the chaser allows controls of both facilities at the same time. Interactions and hand-over between rendezvous system and robotic capturing system can be tested.

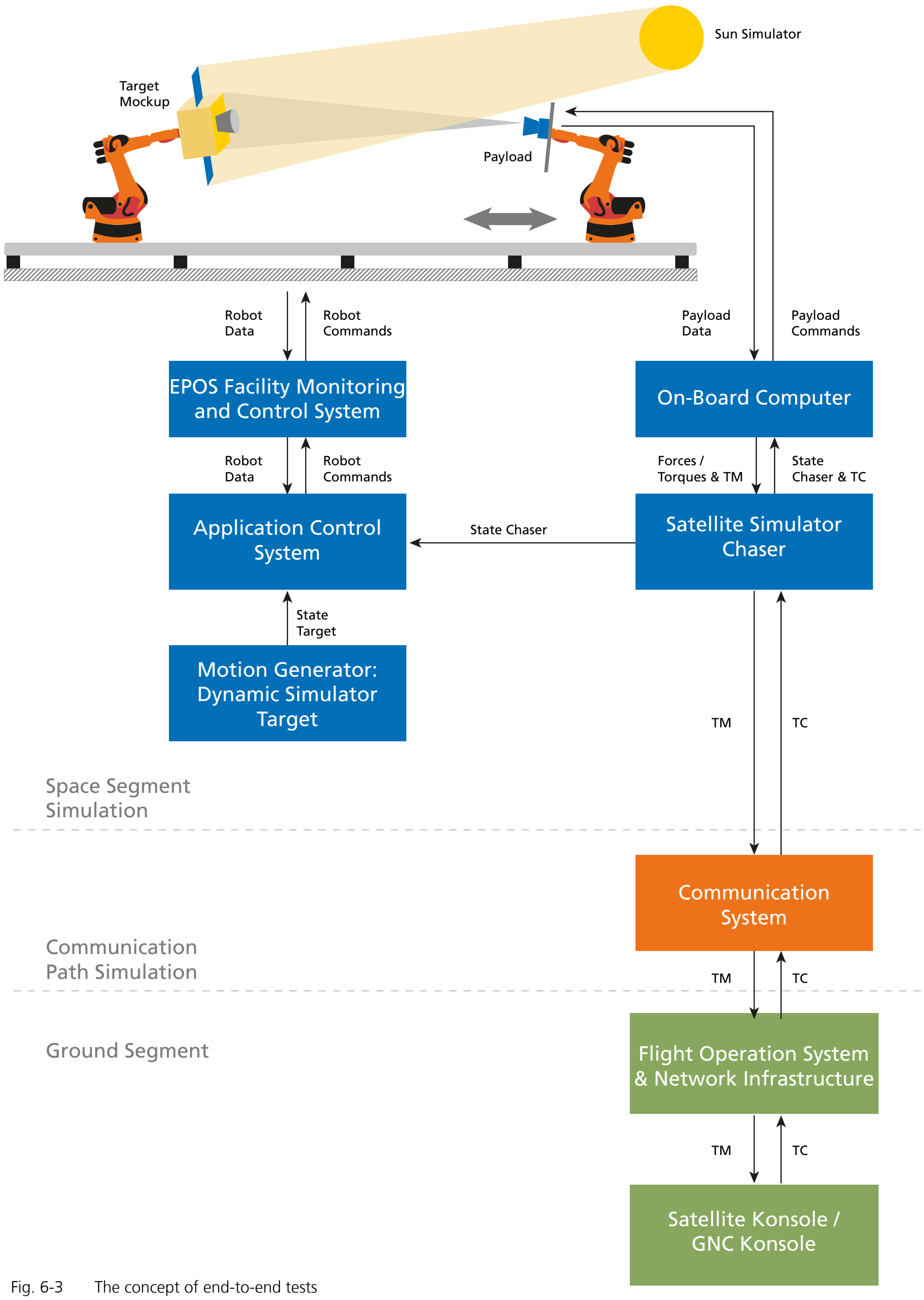


Fig. 6-3 The concept of end-to-end tests

7. Test Organization

The test campaigns are divided in test proposal, test preparation, test execution and test documentation and support of test analysis. Each test campaign is individual and adaptations (software and sometimes also hardware) can be implemented for the specific needs of the project.

The test proposal phase usually contains:
- Definition of the project goal
- Definition of the items to test (sensors, processors, target mockup)
- Definition of the category of the test (open-loop, closed-loop, end-to-end)
- Definition of the test duration
- Estimation of the costs

The test preparation phase contains:
- Definition and implementation of trajectories or of simulation software
- Clarification on interfaces, integration of test equipment
- Adaptation of application control system if needed
- Risk analysis and implementation of safety measures if needed
- Preparation of test protocols and test procedures
- Execution of pre-tests
- Documentation (test specification).

The test execution phase contains:
- Mounting of the test equipment of the customer/partner
- Sensor calibration
- Execution of the tests according to the test procedures
- Generation of test data and test protocols
- Generation of videos etc.

The test documentation and test analysis phase contains:
- Documentation (test report)
- Support for test analysis

Test can be organized in this classical way, but also in an agile way. Especially for complex test cases or projects where the tests cannot be planned in advance because they might depend on the result of future research, the test can be organized in iterative circles with several test executions.

It is possible to first test a simple prototype, to plan the next developments after the first test has been executed and to test an advanced version later (plan – do – act – check cycle).

Test campaigns are planned, prepared and executed together with the EPOS-team of DLR space operations and astronaut training.

8. Exemplary Test Setups

A typical setup is as follows: Robot 1 on the linear rail carries rendezvous sensors. The sensors can be mono cameras, stereo cameras, scanning LiDARs, flash LiDARs, and many more. Robot 1 performs approaches by moving linearly along the 25m slide. Robot 2 carries the target. This can be the outer surface of a satellite or part of the outer surface, a debris object, a sample, or part of the outer surface of a space station (like docking port of the ISS). The target can also consist of a pattern of LEDs or retro-reflectors. Also combinations like a satellite mockup with retro-reflectors are possible. The Sun is simulated at EPOS with a 12 kW spotlight (ARRI MAX 12/16). In principal also other spotlights can be used. For some missions, the GNC concept also contains artificial illumination systems. These can be integrated at the adapter plate of Robot 1 next to the sensors.

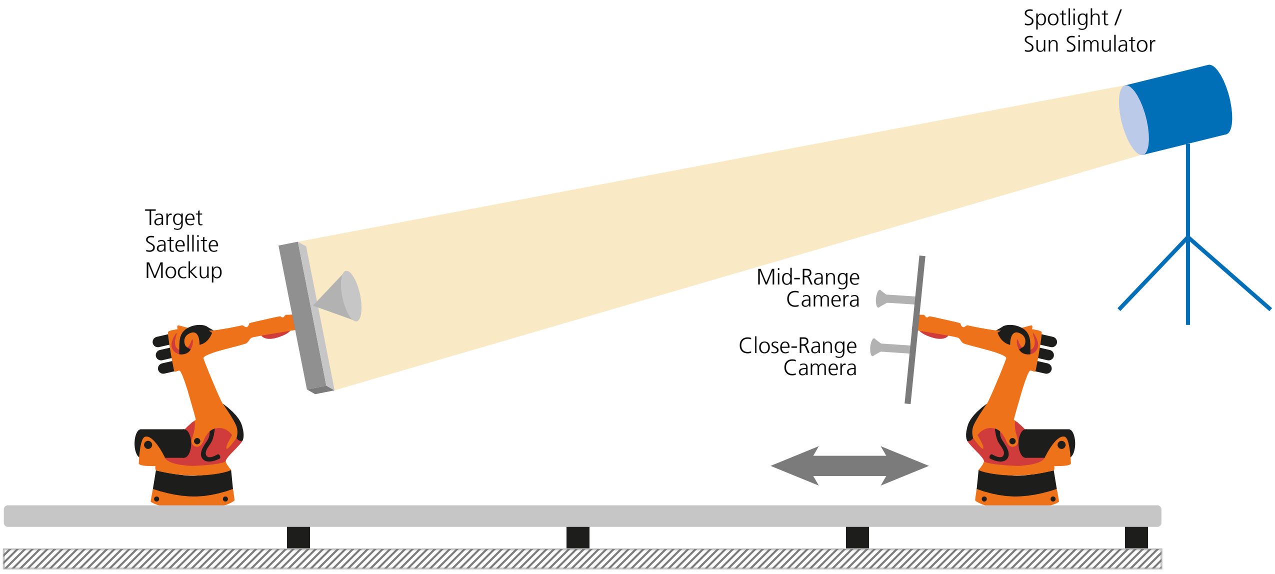


Fig. 8-1 Example 1: a simulation of a lifetime-extension mission with two cameras with two different optics as sensor system, and with a satellite mockup as target. The Sun is simulated with a spotlight.

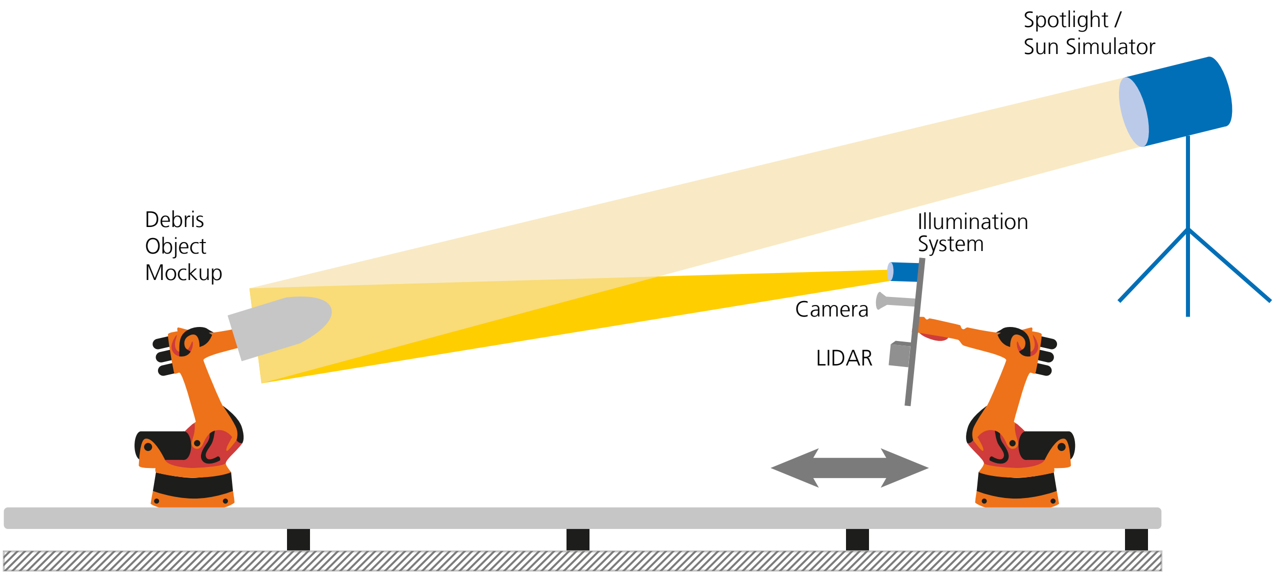


Fig. 8-2 Example 2: a simulation of a debris removal mission with a camera and a LiDAR as sensors, and with a debris object as target. An artificial illumination system is further installed. The Sun is simulated with a spotlight.