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EROSS project – Ground validation of an autonomous GNC architecture towards future European servicing missions

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Abstract

The emerging On-Orbit Servicing market is evolving at an unprecedented pace over the last years, driving the related European robotic technologies into a fast and agile development to meet these new needs. With that respect, the EROSS project led in the scope of the H2020 framework integrated and demonstrated the performances of an overall Servicer design towards the future on-orbit services like life extension, refuelling, and even the more futuristic scenario of a unit exchange for repair or upgrade. This paper presents the EROSS mission of application and the overall hardware and software architecture which has been validated at functional, kinematic and dynamic levels. The focus of the presented work is on the results of these experiments with orders of magnitude of the attainable performances and the level of autonomy implemented. Both open and closed loop experiments are presented along with their respective validation scope regarding the overall Servicer and Client designs. The goal of this experiments is to raise these technologies maturity towards an in-orbit demonstration by 2025.

1. Introduction

Space robotics has known an intense acceleration of its developments over the last five to ten years with the impulse and rising of new markets such as the On-Orbit Servicing (OOS) or the autonomous In-Orbit Assembly (IOA) of space structures. This first kind of mission became a reality on February 26th, 2020 with the premiere of an on-orbit service by a Servicer to a Client spacecraft when Northrop Grumman successfully docked their Mission Extension Vehicle-1 (MEV-1) vehicle to the Intelsat 901 (IS-901) spacecraft to extend its life duration at a geostationary slot*.

With that respect, the European Commission is leading the Strategic Research Cluster (SRC) in Space Robotics to boost the maturity and the synergy of both industrial and academic European actors in this domain. Since 2016, three main suites of projects, also called “Operational Grant” (OG), have been led with a first set from OG1 to OG6 in 2016-2019 to develop robotic building blocks [1]-[5], and a second set from OG7 to OG11 to integrate them towards orbital/planetary missions from 2019 to 2021 [6]-[8]. The last step is now engaged to mature the mission of demonstration described in [9] with the last OG12, OG13 and OG14 [10], as illustrated in Figure 1.

Within this Space Robotics SRC, Thales Alenia Space has led the OG4-I3DS on smart sensors development, the OG7-EROSS on the ground validation of a servicing mission, and is now leading OG12-EROSS+ to lead the system phase A/B1 towards an OOS mission of demonstration.

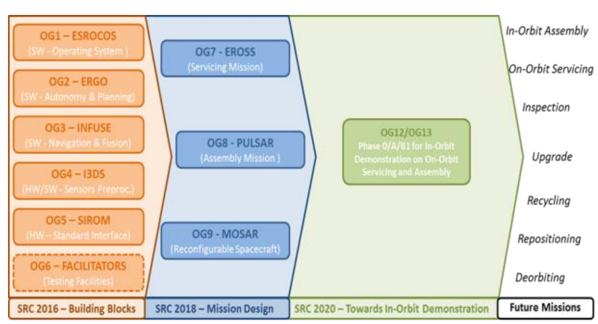


Figure 1 - Workflow of past and present Operational Grants within the SRC in Space Robotics

* [last access: 12/05/2021] https://news.northropgrumman.com/news/releases/northrop-grumman-successfully-completes-historic-first-docking-of-mission-extension-vehicle-with-intelsat-901-satellite

More specifically, the H2020 project "European Robotic Orbital Support Services" (EROSS) was led to mature an autonomous Guidance, Navigation and Control (GNC) architecture for future robotic servicing missions, including the interface with real hardware. In this regard, EROSS project aims at developing, integrating and demonstrating the key European robotic building blocks within an autonomous solution for the performance of servicing tasks.

The paper presents the final experimental validation of the EROSS project whose preliminary numerical validation results were already presented in [12] and are available online in [11]. The paper is organized as follows: (1) an introduction is given on the H2020 and SRC context; (2) a description of the mission of application is given before (3) focusing on the vehicles design and their mock-up versions; (4) the validation plan is then described along with the overview of the (5) functional integration tests, (6) the dynamic validation on an air-bearing table, and (7) the kinematic validation on a robotic test bench with a hardware/software closed-loop demonstration.

2. Mission Description

The focus of the EROSS project is on the last step of a traditional rendezvous missions. It covers the forced motion, the berthing, and servicing operations, while the initial orbital manoeuvers to phase it within the Client orbital plane and to synchronize its true anomaly are considered already performed [12].

The EROSS scenario demonstrated by experiments can be split into two main phases to cover the final rendezvous and capture steps:

- **Phase E - Mating**: final approach, station keeping, coordinated/compliant robotic capture, composite stabilisation;
- **Phase F - Servicing**: berthing, refuelling, robotic exchange of a replaceable unit.

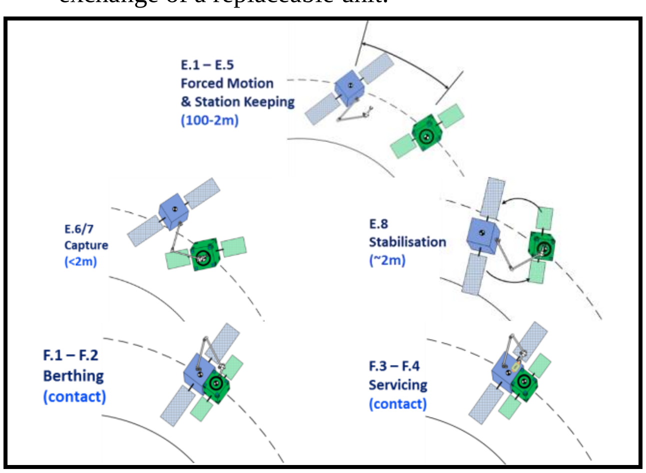


Figure 2 - EROSS Mission Description with (E) approach & capture, (F) berthing & servicing

The emphasis is put on the autonomous performance of the medium and close-range manoeuvres of the rendezvous, along with the capture and manipulation of the Client satellite. This latter is considered "collaborative" and "prepared" for servicing operations. EROSS timeline is based on five following steps illustrated in Figure 2 :

- (E.1-5) the approach with an autonomous visual-based navigation;
- (E.6-8) the capture based on compliant and coordinated control techniques to synchronize the robotic arm and the platform;
- (F.1-2) the mating of the two spacecraft;
- (F.3) the refuelling of the Client;
- (F.4) and the robotic exchange of a replacement payload designed with standard interfaces.

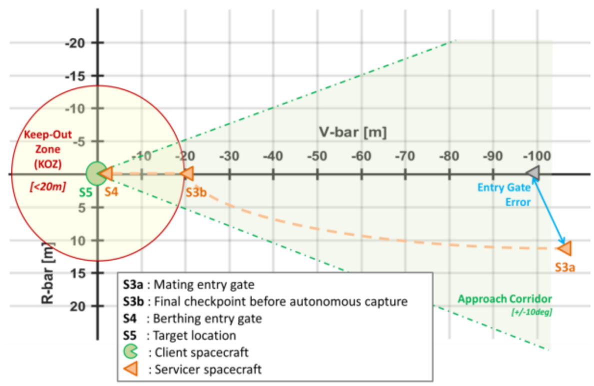


Figure 3 - EROSS final forced motion to approach and capture the Client vehicle

The EROSS Servicer space robot must then fulfil the following functions, whose details are summarized in Figure 3 with respect to the Client local orbital frame, :

- **Final Approach**: The Servicer is already tracking the Client within its sensors FoV. It performs a continuous forced motion to approach the Client along a straight line;
- **Berthing**: This is the first step of the coordinated control with the Servicer platform maintaining a relative berthing position and attitude with respect to the Client while the robotic arm is deployed and move towards the grasping feature to capture it;
- **Servicing**: Once the two platforms are rigidly linked through the robotic link, the Servicer mates with the Client by reconfiguring its robotic arm and plugging the refuelling interface. Two types of servicing are then demonstrated with the refuelling through the ASSIST interface and the exchange of an Orbital Replacement Unit (ORU) equipped with two SIROM standard interfaces to dock on the hosting platforms;

- **Release**: Following the same steps in the opposite order, the two spacecrafts are eventually released after a grasping, interface release, and eventually separated by the robotic arm before the natural laws of orbital dynamics and a single boost manoeuver take the Servicer away from the Client in a safe way.

3. Vehicles Design & Mock-up

The design of the Servicer and Client vehicles is based on a long heritage from both R&D studies and scientific programs led by Thales Alenia Space: the Servicer is based on a compact octagonal shape allowing to minimize its volume for launch and safety reasons, while the Client is based on the Sentinel-3 spacecraft whose design has been slightly adapted for this servicing demonstration.

Hereunder, an illustration is given in Figure 4 of both the theoretical vehicle design in the early phases of the project, while Figure 5 shows their equivalent mock-ups designed for the experimental demonstrations.

Figure 4 - Illustration of EROSS Servicer and Client vehicles from the mission perspective

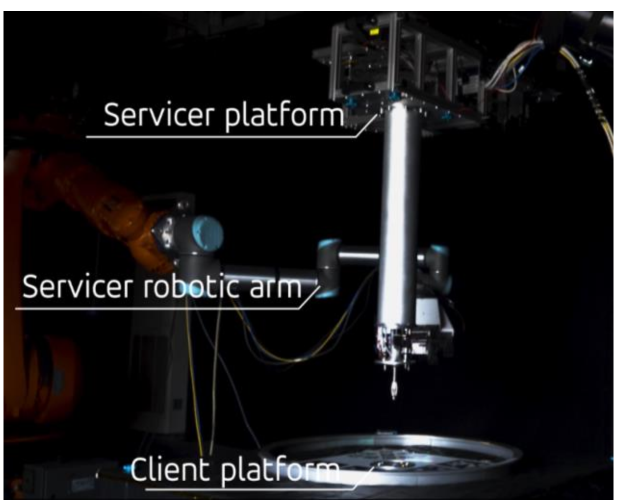


Figure 5 - Illustration of EROSS Servicer and Client mock-ups from the experimental perspective

3.1. EROSS Servicer

The Servicer design is optimized towards future servicing missions and is the result .of multiple studies led by Thales Alenia Space with the CNES and ESA space agencies, as well as with internal funds.

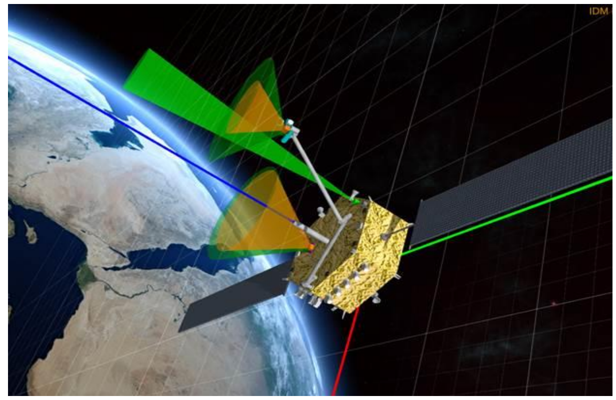


Figure 6 – EROSS Servicer mission design with its robotic arm and rendezvous and robotic sensors Fields-of-View

As seen in Figure 6, its hexagonal platform of less than 5 m of diameter and 2 m height allows it to reach a compact form factor. This shape stems to the compact volume constraints to ease the attitude control and clearance for rendezvous and capture, but also to maximize the upper panel for the robotic bay. This upper side is dedicated to the robotic equipment for rendezvous functions: the refuelling interface on top of a mast, the relative rendezvous sensors, and the robotic arm with its own set of sensors at the end-effector.

The lateral parts are composed of 6 panels. On two of them, the rollable solar arrays are accommodated diagonally opposed. They have been developed by Thales Alenia Space in France over the last ten years. This innovative solution is required as the electrical propulsion choice implies high power for orbital transfer phases as well as during the servicing phase to feed the Client with electrical power. On the opposite, the Servicer requires much less power during the rendezvous and capture phase, when the solar panels are rolled in stowed position to maximize the clearance and minimize the risk of collision during the robotic motion. Two of the lateral panels are dedicated for the Orbital Replaceable Units (ORUs) depending on the mission scope and number of Client to be serviced. For this purpose, it accommodates 10x standard interfaces on the Servicer platform, with a payload capacity of 9x ORUs loaded for the launch configuration. Each of them is assumed to be exchanged with a serviced Client to either repair or upgrade its payload or its faulty equipment. One slot is left free to handle the unit transfer with the Client during the servicing.

The Servicer On-Board Software (OBSW) and GNC design inherit from the past H2020 projects mentioned above with the past Operational Grants (OG). It reuses and integrates:

- the ESROCOS software layer from OG1 [1] and the ERGO autonomy framework of OG2 [2] both developed by GMV,
- the INFUSE data processing of OG3 [3] developed by Space Applications Services,
- the I3DS sensors integrated through an ICU processing board within OG4 [4] developed by Thales Alenia Space with the complete software (SW) integration by SINTEF,
- the SIROM standard interface from OG5 [5] developed by SENER,
- and the validation facilities from OG6 handled by GMV for the orbital tests.

In addition, the EROSS project also integrates customized elements such as the robotic arm designed by MDA, the ARAMIS rendezvous sensor developed by SODERN, the ASSIST docking and refuelling interface by GMV, and a capture gripper developed by PIAP-Space.

The resulting mission design illustrated in Figure 6, while the final mock-up design is given in Figure 7. The mock-up design has been mainly driven by the payload constraints of the robotic arm used on the validation test benches, along with the functional needs of EROSS demonstration. This focus on ground validation led to focus the mock-up design on the key equipment being validated and not on the representative external shape, as this was not meant to be seen during the different mission steps. The mock-up is thus reduced to a structural skeleton scaled down with respect to the mission design, and to the main rendezvous cameras, flash, projector and refuelling interface [6]-[12].

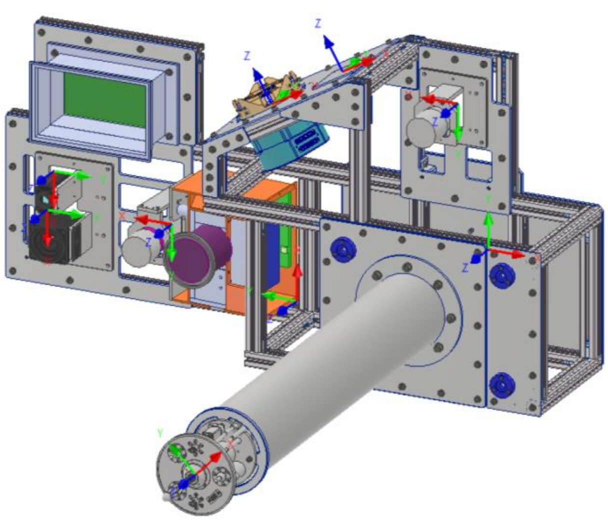


Figure 7 – EROSS Servicer mock-up design with the reference frames of each equipment

3.2. EROSS Client

The Client spacecraft considered within EROSS project is derived from the Sentinel-3A spacecraft developed by Thales Alenia Space. More elements on his design and mission of application are available in [12] and [15]. Its final design following the EROSS adjustment for the servicing mission is illustrated below.

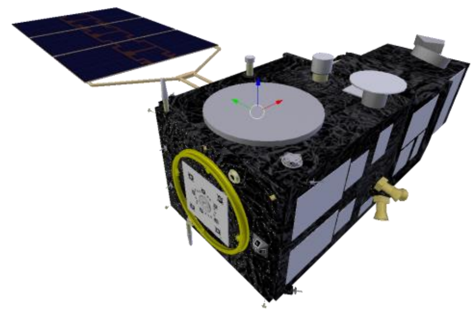


Figure 8 - Illustration of the EROSS Client satellite with markers and refueling/standard interfaces

In the scope of the EROSS use case, the Sentinel-3A design has been slightly adapted to allow the Client satellite to be **prepared and cooperative** at the time of its servicing. It features the following "servicing ready" adaptations to ease the rendezvous & capture and to make possible the servicing tasks with the proper interfaces:

- An ASSIST passive interface is located inside the Launch Adaptor Ring (LAR) perimeter (in yellow) in order to perform both the mechanical mating between the platforms and the refuelling service,
- A SIROM standard interface is located on the payload structural panel (on the top) to perform the ORU exchange with the right interface on both Servicer and Client sides,
- Passive rendezvous aids (e.g. reflectors and paintings) are dispatched at several locations on the client satellite surface and particularly onto LAR panel and ASSIST passive interface to ease the relative motion at very close range only.

The mission design of the Client vehicle is illustrated above in Figure 8, but two different mock-up versions have been produced within the EROSS project considering the test bench and equipment constraints. Indeed a unique mock-up would have necessarily been at scale 1:1 to integrate the robotic interfaces prototypes at full scale. But a 1:1 mock-up would have limited the Navigation sensor testing to the kinematic test bench length around a dozen of meters. Instead, a second mock-up at scale 1:3 has been designed and produced to allow a navigation validation from contact up to 36m, being thus representative on a much longer trajectory.

In the following images these two mock-up designs and resulting hardware are given. The two version have been respectively called "Long-range mock-up" for the smaller mock-up at scale 1:3, and "Short-range mock-up" for the larger mock-up at full scale.

One interesting feature of the Long-Range mock-up is to be designed for both visible and thermal sensor validation thanks to the integration of heater around the structure. An illustration of the mock-up design is given in Figure 9, while the resulting hardware is shown in Figure 10, and a thermal calibration of the side heaters is also provided in Figure 11.

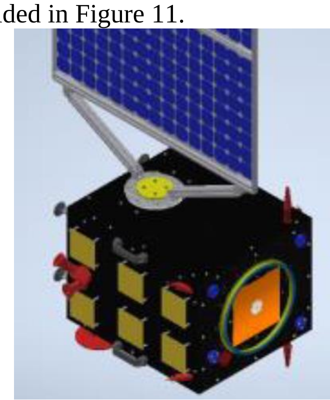


Figure 9 - EROSS Client design in Long-Range configuration for Visual and Thermal Navigation experiments

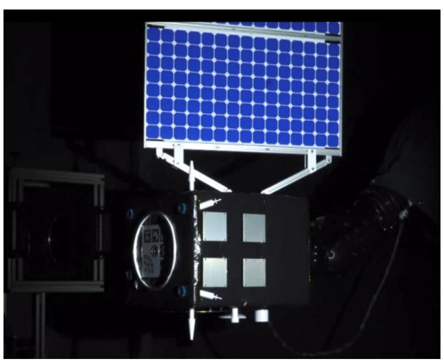


Figure 10 - EROSS Client mock-up in Long-Range configuration

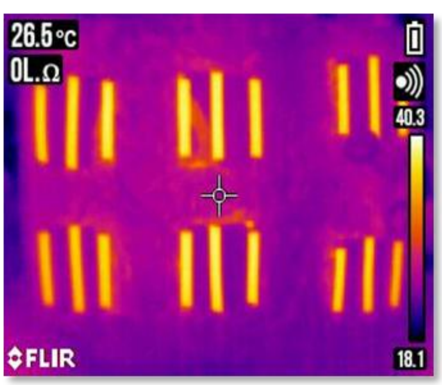


Figure 11 – Squared heaters calibration on the side of the Client Long-Range mock-up

Regarding the full scale version, the Client mock-up was reduced to the spacecraft section actually seen by the relative sensors, to avoid producing a full spacecraft. Hence the rendezvous panel holding the LAR was produced with a depth of 30cm to accommodate the robotic interfaces like the ASSIST refuelling on the centre, a Pyramid of markers along the capture point of the gripper, and the SIROM interface on the top panel illustrated in Figure 12.

Regarding the markers interfaces shown in Figure 13, two main panels are used with : a planar version of large and small markers inside the LAR, and a pyramid version outside the lAR. The pyramide allows to ensure the accuracy of the gripper motion during the robotic capture of the Client based on a visual servoing. On the other hand, the planar markers around the centre allow to maintain the navigation tracking at very short range when the blurring in the image prevents an accurate model-based approach during the the final approach and capture. The smaller markers are used to track the spaceraft mating between the two ASSIST interfaces after the capture, as the camera and marker relative distance shrinks from 2m to half a meter.

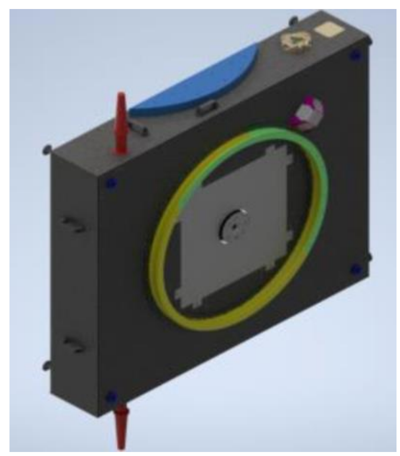


Figure 12 - EROSS Client design in Short-Range configuration for Robotic experiments

Figure 13 - EROSS Client mock-up in Short-Range configuration

4. Validation Approach

Based on the previous EROSS mission and the mock-up design, the validation plan of the different rendezvous and robotic equipment is presented hereunder.

A bottom-up validation approach supporting the EROSS design and development process is proposed in order to check that the Servicer architecture is compliant with the proposed requirements defined in the EROSS project. The following figure presents this traditional bottom-up approach in three main steps to reach the final demonstration tests described in the rest of the current paper.

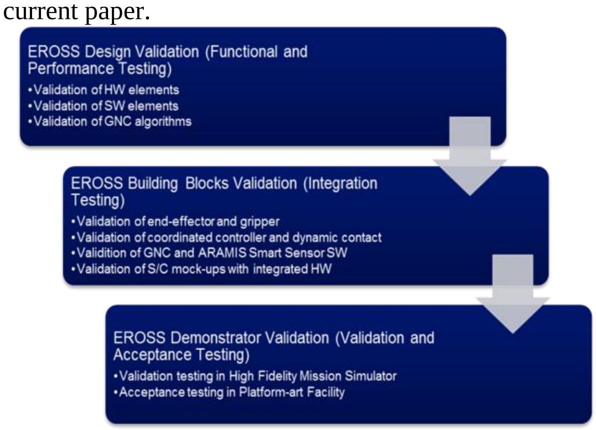


Figure 14 - EROSS Validation Approach with Functional testing, Building Blocks integration, and Validation testing

The following steps were covered during the EROSS validation phase, from the reception of the hardware equipment with their unitary testing to their final integration for the system validation.

- **<u>EROSS Design Validation</u>**. Validation activities for functional and performance testing of each equipment to ensure that their design is compliant with the EROSS functional and performance requirements established for the mission of reference described in Section 2. The main facilities used in this step are the premises of equipment providers.
- **<u>EROSS Building Blocks Validation</u>**. Validation activities related to the integration of the different HW and SW elements before the system validation. The equipment are integrated into building blocks focused on a mission need (e.g., navigation, robotics, interfaces, etc.). These EROSS Building Blocks are validated by cross-checks mixing hardware and software drivers to ensure the proper commanding/measurement from the Robotic Control Unit. The main facility used in this step is the ROBY robotic test bench facility in Thales Alenia Space.
- **<u>EROSS Demonstrator Validation</u>**. Validation activities to achieve the **final integration of the EROSS Demonstrator towards the closed-loop demonstration of the real space mission**. The EROSS Demonstrator was validated incrementally to finally perform the open and closed loop tests. These tests were mainly led in two test bench: the SRE air-bearing test bed at NTUA, and the Platform-Art test bed at GMV. A final validation of the autonomy layer was also conducted in Thales Alenia Space on the ROBY test bench.

This approach has been applied on the two main scaling versions of the EROSS scenario depending on the equipment used for each scaling :

- The Long-range configuration with the Servicer and the Client Long-range mock-ups,
- The Short-range EROSS configuration with the Servicer and the Client Short-range mock-ups.

These two scaling configurations allowed to fully validate the EROSS scenario from the forced motion at 36m (test bench limits compared to the initial 100m from mission definition in Section 2), and recalled in the following Table 1. A switching is made between the two scaling configurations at the berthing location E.5 before engaging the gripper capture performed at full scale. The two configurations allowed to validate the relative navigation sensors and their processing at GNC level, along with the robotic equipment and interfaces with the coordinated robotic GNC architecture [13].

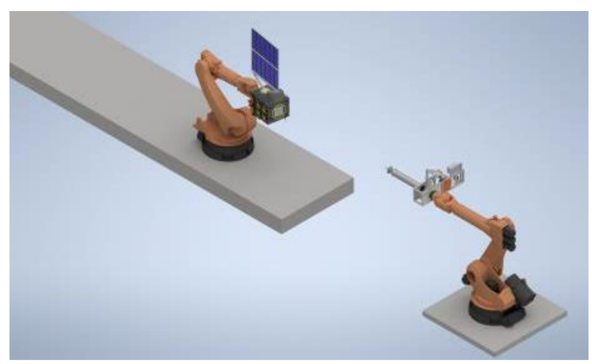


Figure 15 - Long Range Configuration with the Servicer and small Client mock-ups

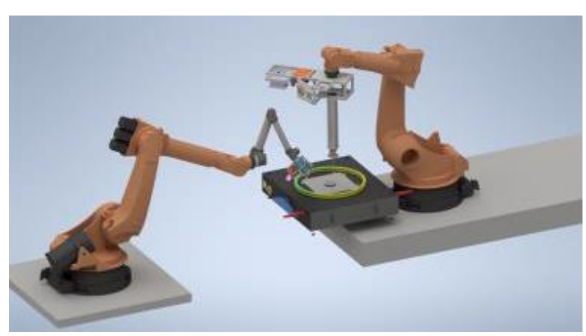


Figure 16 - Short Range Configuration with the Servicer and large Client mock-ups along with the mission Robotic Arm

Table 1 - EROSS Mission Steps and Configurations for the System Validation

Long range approach configuration (E.1–E.4) / Close range approach configuration (E.5–F.4)

Phase	Phase E - Mating OPerations (MOP)							Phase F - Servicing OPerations (SOP)			
Step	E.1	E.2	E.3	E.4	E.5	E.6-7	E.8	F.1	F.2	F.3	F.4
Name	Initialization	Straight line init	Final checkpoint	Straight line final	Berthing position	Floating/Compliant capture	Capture stabilization	ASSIST docking	Arm release	Refueling	ORU exchange
Real Distance : Inter-Platform	36m	36m->20m	20m	20m->2m	2m	2m	2m	2m->0m	0m	0m	0m
Real Distance : EndEff-Target	-	-	-	-	1m	1m->0m	0m	0m	<1m	-	0m
Composite Configuration	Indep.	Indep.	Indep.	Indep.	Indep.	Indep->Arm	Arm link	Docked	Docked	Docked	Docked
Demo Distance : Inter-Platform	12m	12m->7m	7m	7m->0.7m	2m	2m	2m	2m->0m	0m	0m	0m
Demo Distance : EndEff-Target	-	-	-	-	1m	1m->0m	0m	0m	<1m	-	0m
Mockup Scaling	1:3	1:3	1:3	1:3	1:1	1:1	1:1	1:1	1:1	1:1	1:1

5. Functional Validation

5.1. ROBY Integration Test Bench

The ROBotic facilitY (ROBY) test bench of Thales Alenia Space in Cannes (France) has been used for more than 10 years for testing and validation of **rendezvous scenarios** through **real-time simulations**. This facility is based on the coordinated motion of two robotic arms, driven in real time by the dynamic simulations of orbital missions involving two vehicles. It covers the validation of guidance and navigation schemes, as well as the performances assessment for hardware components like rendezvous sensors and actuators.

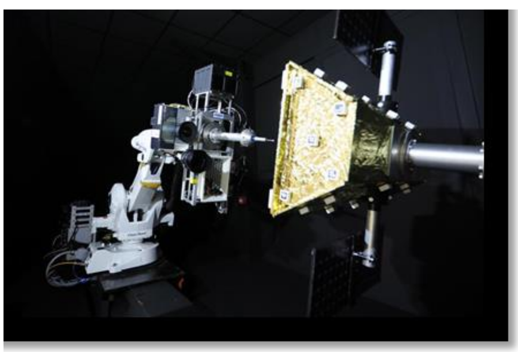


Figure 17 – Robotic Orbital Facility (ROBY) test bench at Thales Alenia Space in Cannes (France)

With two robots of 6 Degrees-of-Freedom (DoF) and a linear rail of 10m, the test bench provides **13 DoFs** to reproduce the different phases of a rendezvous and capture between two spacecraft. In such mission scenario, one element, called “target”, is assumed to be passive, while the second one, called “chaser”, is assumed to be actively controlled to synchronize with and capture the target vehicle.

With respect to the EROSS test plan, the different equipment were received at Thales Alenia Space to be tested unitarily, before integrating them within the reference Building Blocks. It corresponds to the the first two steps of the Validation Plan introduced in Section 4, with the Design Validation and Building Blocks Validation phases.

In the following section, an illustration of this unitary and cross-check is given for the cameras selected for the EROSS demonstration, without going deeper into the similar tests performed for the actuators or other sensors like the pattern projector systems. Apart from equipment testing and integration, their calibration as well was performed on ROBY test bench with the camera intrinsic parameters estimation, the 3D point clouds extrinsic parameters estimation, or the Force/Torque sensor calibration with another reference system.

5.2. Equipment Cross-checks

For a camera integration, the unitary testing covered the check of different low-level functions of the camera with, in particular, the hardware interface check with respect to the Servicer mock-up supports, and the software interface check with the proper data acquisition and data rate.

This first step was the checking of the camera acquisition stability over time through the EROSS Robotic Control Unit (RCU) [4][6][11] with the check of data format, communication protocol and acquisition frequency. As an example, the test performed for one camera is given below around the nominal frequency acquisition of 1Hz, which is the reference Visual based Navigation frequency for the final closed-loop test presented in Section 7.

In the below graph, one might see that the frequency stability remains within the expected margins at GNC and system level with less than 1ms of time deviation in the 1Hz frequency of acquisition.

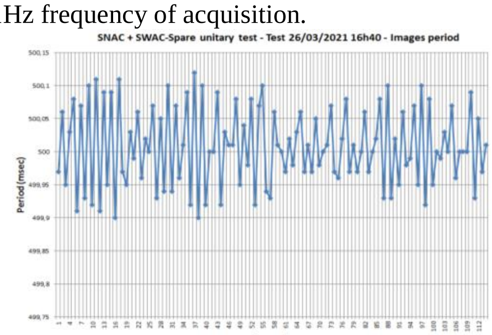


Figure 18 – EROSS SNAC camera unitary test of the acquisition frequency stability over time

Once the two reference cameras for long and short range, respectively the Servicer-Narrow/Wide Angle Cameras (SNAC/SWAC) were tested unitarily, the integrated cross-check covered the performances at a higher level with the time synchronization of both images streams. This latter was crucial to ensure the proper processing of the corresponding images to perform their switching during the approach without degrading or destabilizing the navigation filter. This synchronization was handled by the updated I3DS SW inherited from the OG4-I3DS [4].

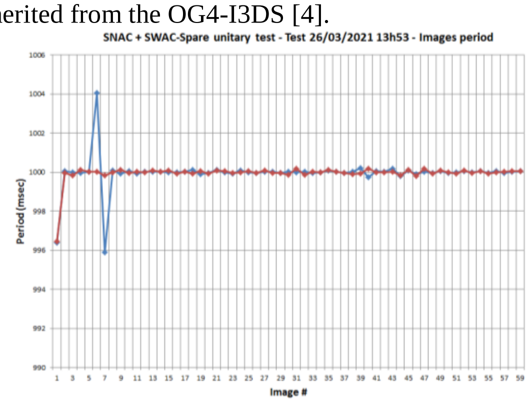


Figure 19 – SNAC/SWAC cross-check with acquisition frequency stability over time [blue - CNAC, red – SWAC]

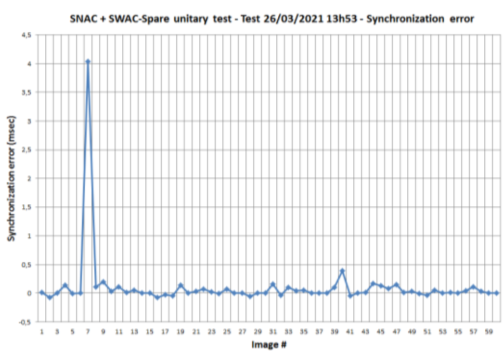


Figure 20 – Time synchronization error between the acquisition of SNAC & SWAC cameras for GNC integration

In the above Figure 19, the frequency stability over time when both cameras are ON at the same time remains nominal below 1ms despite the higher need in bandwidth and data rate at the RCU level. In some isolated worst cases, it can shift to 4ms. Overall, it proves that the RCU architecture at hardware (HW) and software (SW) levels is compatible with the GNC needs.

The second image illustrates the time synchronization between both cameras streams which allows to check that the image processing algorithms running on both camera streams can be fused or without highly disturbing the navigation filter at GNC level. The nominal synchronization error remains below 0.5ms, while some isolated worst cases pushes this error to 4ms. This result is aligned with the advanced multi-rate and asynchronous navigation filter developed in EROSS project to cope with HW/SW delays [12].

5.3. Autonomy Demonstration

Another integrated test has been performed at Thales Alenia Space to fully validate the Autonomy layer implemented through the ERGO agent [2]. This step has demonstrated the autonomy performance of the ORU exchange by the robotic interfaces without including the navigation feedback in the loop. Instead of calling it a "closed-loop" as such, the term of "autonomy loop" demonstration was used in the EROSS project.

The configuration for this test is illustrated below in Figure 21. It consists in the autonomous exchange of the ORU unit from the Client to Servicer or from the Servicer to the Client mimicking the EROSS robotic arm with the ROBY industrial arm carrying the EROSS end-effector with the camera, pattern projector and SIROM standard interface. Connected to the end-effector is the ORU unit with the gray box, whose opposite end is also connected to the Client Short-range mock-up. This configuration allowed to check both the robotic visual servoing performance reported later in the paper, and the autonomous exchange of the ORU combining the SIROM & ORU interfaces commanding through the RCU unit, and the robotic trajectory generation and execution through the robotic GNC algorithms in the On-Board Computer (OBC).

In the same image, the Servicer mockup without the refuelling interface is also seen at the base of the industrial robotic arm, along with the Client Long-range mock-up. This parallel setup allowed for the previous cross-checks of the various Servicer cameras, along with the image processing techniques performances.

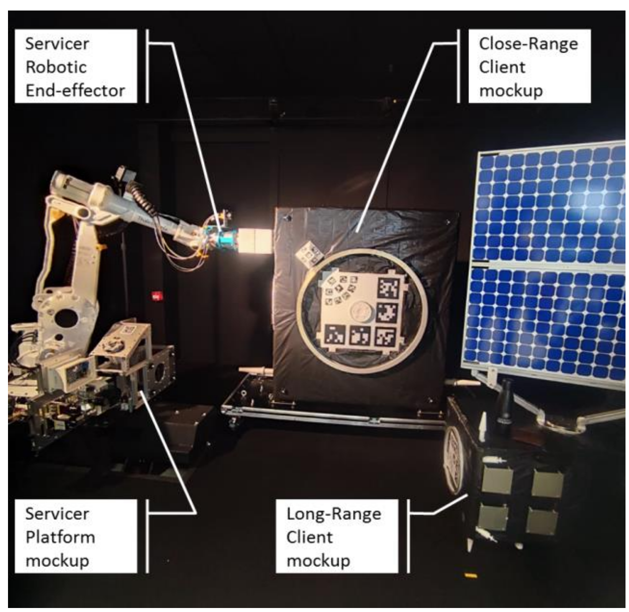


Figure 21 – Autonomy loop setup on ROBY test bench for the demonstration of the ORU exchange service

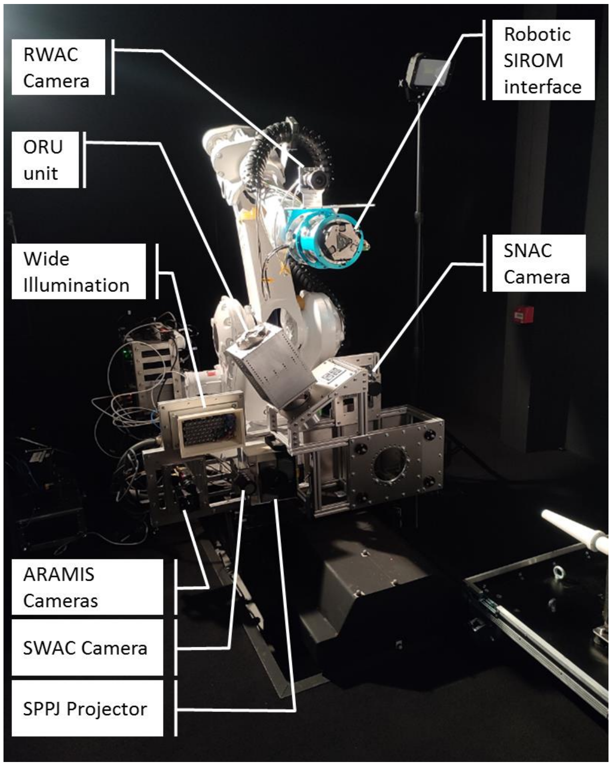


Figure 22 – Servicer Platform & End-effector setup on ROBY test bench for the Autonomy loop demonstration

In Figure 22, the Servicer platform and its end-effector are illustrated into more details. The different equipment tested in this phase are clearly visible with the Robotic Wide Angle Camera (RWAC), the SIROM standard interface and the ORU unit. This three elements along with their drivers and processing software were the key Building Blocks of the Autonomy loop validation used for the ORU exchange in full autonomy.

The main steps of this demonstration are illustrated in Figure 23 with the following HW/SW synchronization performed between the RCU and OBC functions:

1. Alignment of the end-effector by tracking the robotic Guidance reference on OBC side to reach a key point 10cm above the SIROM interface of the ORU;
2. Approach in straight line of the “SIROM.r” on the end-effector until the contact is reached, and SIROM connection is monitored by the RCU;
3. Disconnection of the ORU by commanding the SIROM on the mock-up side to disconnect, still monitoring from the RCU;
4. Motion to the next key point 10cm above the Servicer SIROM interface denoted “SIROM.s”, by tracking the robotic Guidance reference on OBC side;
5. Approach of the ORU in straight line until the connection between its SIROM and the SIROM.s is validated by the RCU;
6. Retraction of the end-effector along a straight line 10cm above the ORU and then to a safe station keeping position, following the reference Guidance profile from the OBC.

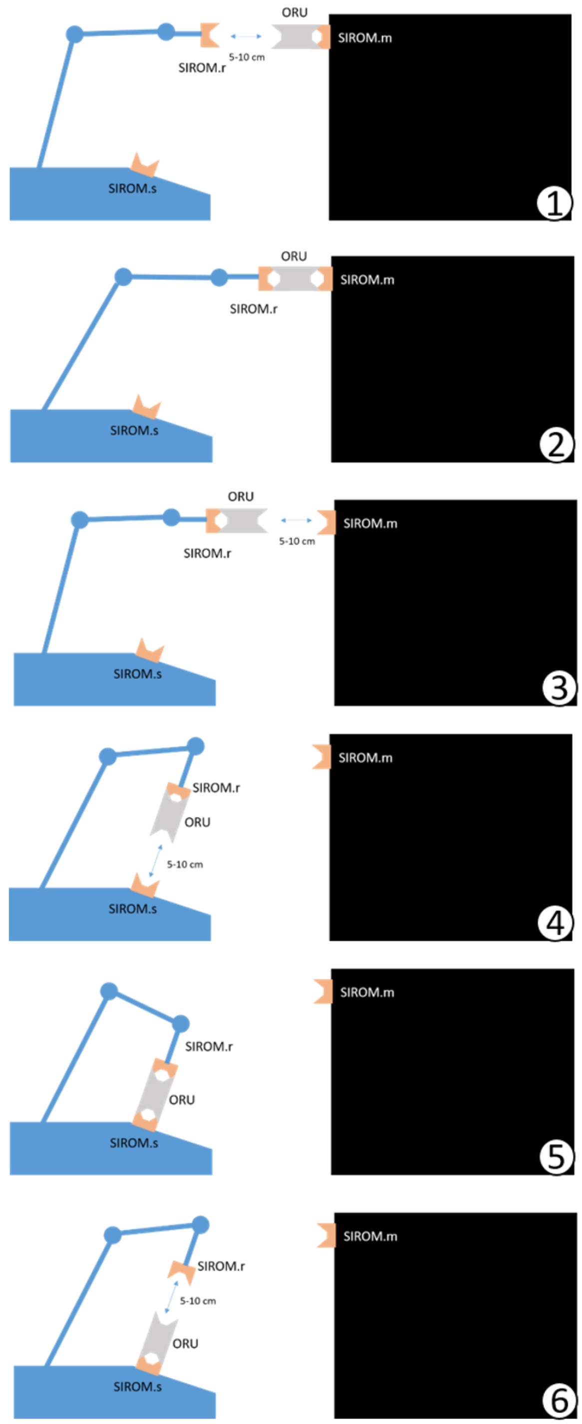


Figure 23 – Steps of the Autonomy loop demonstration with the ORU exchange managed from the RCU and OBC units

6. Dynamic Validation

The next section is dedicated to the system level tests with the EROSS Demonstrator being fully integrated and cross-checked. In the following dynamic tests, the focus is set on the robotic GNC loop with its validation in 2D floating conditions including the gripper and the ASSIST functional mock-up used respectively to capture the Client and its Launch Adaptor Ring, and then to mate the two spacecraft before releasing the arm.

6.1. SRE Air-Bearing Test Bench

The test bench used for this test is the Space Robotic Emulator (SRE) developed by the National Technical University of Athens (NTUA) in Athens (Greece).

It consists of a blue black hard rock table with floating systems, workstations and other peripheral devices required for the operation (PhaseSpace mocap system, overhead camera, etc.). The emulator is located at the basement lab of the NTUA-CSL (Computing Systems Laboratory) in order to eliminate as much as possible any residual vibrations from the environment. The larger part of the emulator is the hard rock table of extremely low roughness (about 5 μm mean value), of 2.2 m length and 1.8 m width (about 4 m^2 of surface in total). Satellite/ robot mock-ups, equipped with CO2 tanks can float on the table using air bearings. The air bearings lift the robots about 10 μm thus providing essentially frictionless motion over the table. Since the robots are fully autonomous, there are no external disturbances, resulting essentially in zero-g planar motion emulation. Around the hard rock table, a number of workstations are dedicated for telemetry and control of the floating robotic systems. The NTUA-CSL SRE is comprised of two active, autonomous robots, and one autonomous passive robot, all of adjustable mass and inertia. Both active robots can translate using 3 or 4 pairs of thrusters and can rotate using either their thrusters or their installed reaction wheel. Depending on the required task, it is possible to change the current manipulator end effector to install an appropriate tool and/or to install the necessary equipment.

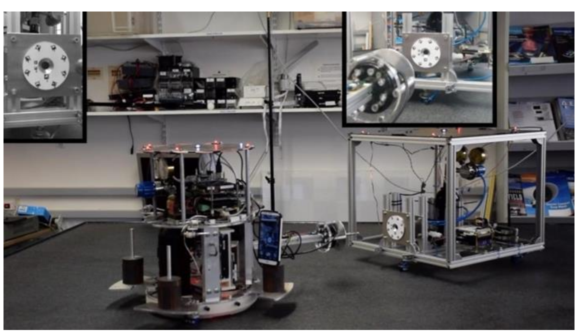


Figure 24 – Chaser robot approaching the Target robot during the ASSIST Dynamic Tests at the NTUA-CSL SRE test bed [ASSIST Project]

6.2. Dynamic Test Overview

For the needs of the EROSS experiments, the active robotic system named “Cepheus”, emulates the Servicer after being adapted with the new equipment from EROSS project and after being re-calibrated from the Mass, Center of mass, Inertia (MCI) perspective. The EROSS configuration of Cepheus vehicle is illustrated in Figure 25.

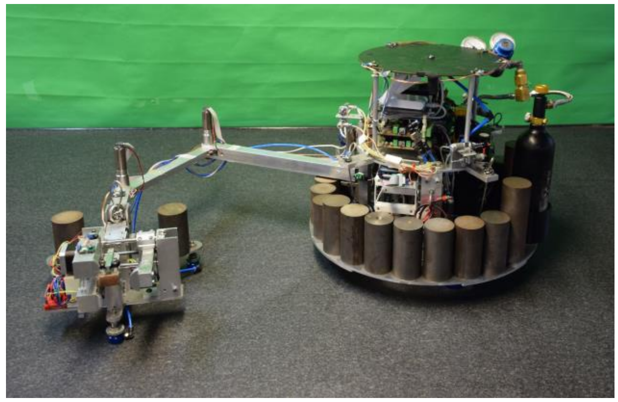


Figure 25 – Free-floating EROSS Servicer mock-up based on the Cepheus vehicle with the gripper functional mock-up

In particular, the initial system had 3 pairs of thrusters (not to be used in EROSS experiments), a Reaction Wheel (RW), a robotic manipulator with 2 Degrees of Freedom (DoF), power autonomy, computational autonomy, and sensors providing its position and rotation on the SRE. However, due to the large dimensions and weight of EROSS gripper, it was necessary to manufacture a new larger manipulator and increase the weight of Cepheus base (see the numerous wheights at the Cepheus base above). This adjustment was necessary (a) due to the dynamic coupling between the Gripper bearing manipulator and the Base of Cepheus and the resulting Base disturbances and singularities, and (b) due to the light design of the initial manipulator, it would have been impossible to control the position of the Gripper with the required precision, while at the same time, the initial manipulator would be impossible to move the mass of the Gripper.

In order for the manipulator to hold the Gripper, a Gripper Base has been developed. To avoid a turn-over of the Gripper, the Gripper base is designed to have its own Air Bearings; this in turn resulted to an increased consumption of CO2, which required the use of a second CO2 tank on Cepheus’ Base.

Finally, to perform initial functional tests, a simple custom-made gripper with “open/close” states has been developed, and is illustrated in Figure 25. This gripper was removed from the Gripper Base, when tests with the EROSS Gripper took place.

The Client system is based on an existing 24 kg passive system of the SRE illustrated in Figure 26. A LAR mockup has been manufactured and placed at one side of the Client, while an ASSIST-like drogue system has also been installed. The LAR and the ASSIST drogue are fixed to a F/T sensor during the two Dynamic Tests in order to counter-measure the end-effector measurement during the grasping of this LAR.

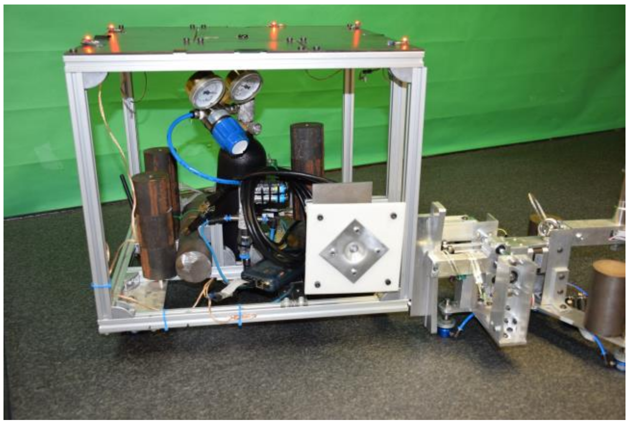


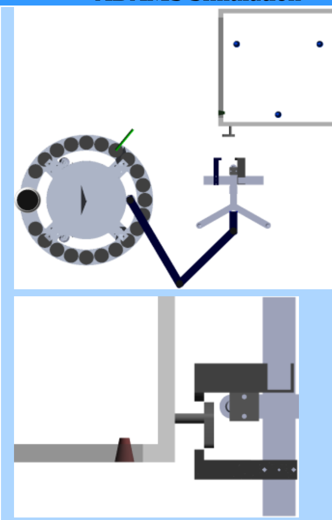
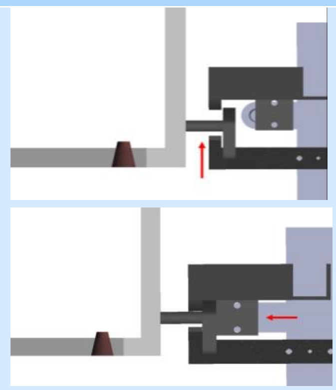
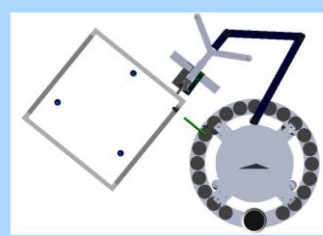
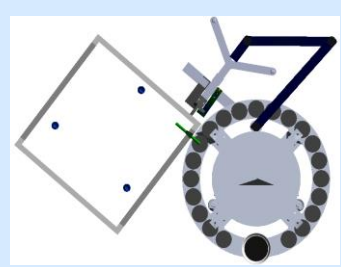
Figure 26 – Free-floating EROSS Client mock-up based on a passive vehicle with the LAR and ASSIST interfaces

Regarding the validation plan of these dynamic experiments, two main steps were tested, as summarized in the following Table 2.

- **The *first Grasping Test*** focuses on the approach for the Gripper to topologically enclose the LAR mock-up and then proceed with the Soft and Hard Grasping, using the Inertial Cartesian-space Compliant Controller (ICCC) developed at the robotic GNC level in order to control in a coordinated way the gripper motion and the Servicer platform attitude (see [13] for more details).
- **The *second Docking Test*** focuses on pulling the firmly grasped (by the LAR) Client close to the Servicer, where the ASSIST Probe is located, and inserting the Probe in the Drogue of the Client (Docking), using the Relative Cartesian-space Compliant Controller (RCCC) in order to control in a coordinated way, both the grasped Client motion and the Servicer platform attitude [13].

The different steps are performed to ensure the maximum of safety during this experiment with contact dynamics. Hence the Force/Torque measurements are always correlated with a ground truth measurement on the passive Client mock-up side to ensure that the experiment can be stopped at any time. In addition, this safety measurement also helped the integration and cross-check of the gripper Force/Torque in the GNC loop.

Table 2 - Steps of the Dynamic Tests for Grasping and Docking of the EROSS Servicer and Client vehicles in floating conditions

	Description	ADAMS Simulation
Grasping	The end-effector motion with ICCC controller to align with the LAR interface for capture, while keeping the Servicer platform attitude constant. The ICCC controller is used, to compensate for the dynamic interactions.	
	The gripper is commanded to perform soft and hard capture to rigidly handle the Client vehicle and to stabilize the composite system. The ICCC controller is still used to compensate for the dynamic interactions.	
Docking	The Servicer moves the Client by the robotic arm to align both ASSIST interfaces for mating the two platforms. The RCCC controller is used to keep the Servicer platform attitude constant during the composite robotic motion.	
	Once the two ASSIST interfaces are aligned, the active ASSIST interface is commanded to open the Probe pantograph system within the Drogue cavity to secure the rigid connection between the two platform, and to disconnect the gripper from the LAR and release the robotic arm.	

6.3. Dynamic Test Results

Some of the test outputs are presented hereunder in a partial version due to the paper length constraint. More results are available on the project website [11], where public documentation has been made available.

As an illustration of the results obtained, the following graphs in Figure 27 show the resulting Force/Torque measured during the experiment of Grasping Test, with Servicer Gripper grasping the Client LAR interface. The ICCC controller used during this test allowed to validate the proper coordination of the robotic motion along with the Servicer base. As a result, a very smooth capture is performed with forces at the impact remaining below 5N, while the torques are so small that they are below the minimum measurement resolution of the sensor. This result was achieved by adapting the speed of approach and by tuning finely the ICCC controller with the final MCI properties of the EROSS Servicer mock-up.

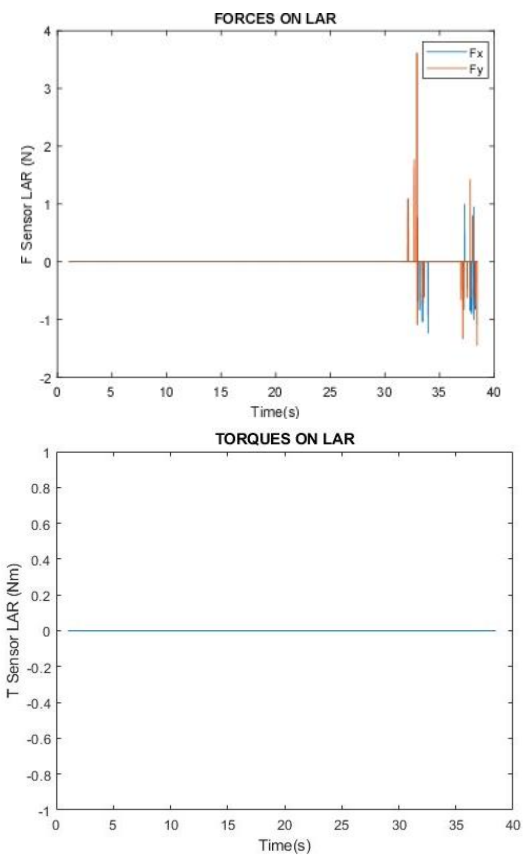


Figure 27 – Resulting Force/Torque measurements at the gripper level when capturing the Client LAR for the EROSS grasping experiment

In parallel to this effort measurement, the motion of the gripper was also tracked to check the accuracy of the robotic GNC loop with respect to the reference Guidance trajectory from the OBC in Figure 28. The error remains in the order of a few centimeters, being compatible with the constraints of the Gripper capture envelope with the open fingers, and remaining compatible with the system requirements defined in the EROSS project.

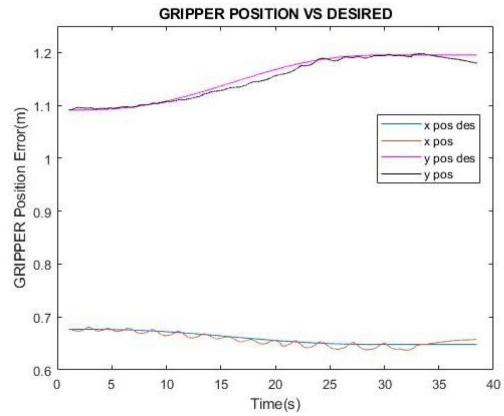


Figure 28 – Gripper reference VS actual position when capturing the Client LAR during the Grasping Test

In the same way, the orientation of the Servicer base (i.e., the Cepheus vehicle introduced above) was closely monitored by the mocap system to ensure that the coordinated controller was effectively maintaining the platform attitude. On the following figure, the experiment demonstrated that the resulting error was below 5deg for the worst cases (i.e., a deviation of 0.1rad wrt the initial attitude to be maintained), while the last seconds of the experiments illustrates the capture impact on the base orientation. During this experiment, the main goal is to ensure the quick and accurate capture by the robotic arm, while the base motion is controlled in a slower manner not to interact too much with the robotic GNC loop, hence this attitude deviation that can seem large at first sight. This test alos validated the stability of the robotic controllers as the Servicer alone and then the composite system are properly controller.

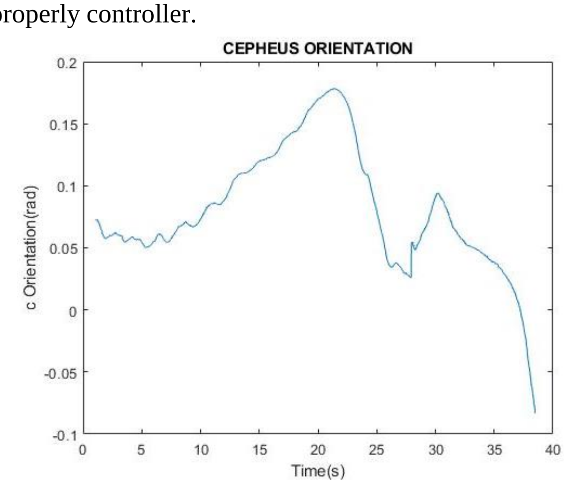


Figure 29 – Servicer base orientation error when capturing the Client LAR during the Grasping Test

7. Closed-Loop Validation

The final system-level test has been performed with the fully integrated Servicer and Client mock-ups along with their respective equipment. This test was a so-called "kinematic validation" in the sense that the dynamics of the industrial robotic moving the mock-ups is not representative of the floating dynamics, as for the SRE bench, but the dark and cold environment is representative of space conditions to validate a Navigation chain and above all the overall EROSS GNC architecture in closed loop. This last test described below is thus mixing Hardware-in-the-Loop (HiL), Processor-in-the-Loop (PiL) and Software-in-the-Loop (SiL) experiments by demonstrating the EROSS architecture in closed loop.

It is worth highlighting that this experiment is the unique combination of all the past OGs developed in the scope of H2020 project in the SRC in Space Robotics, as illustrated below.

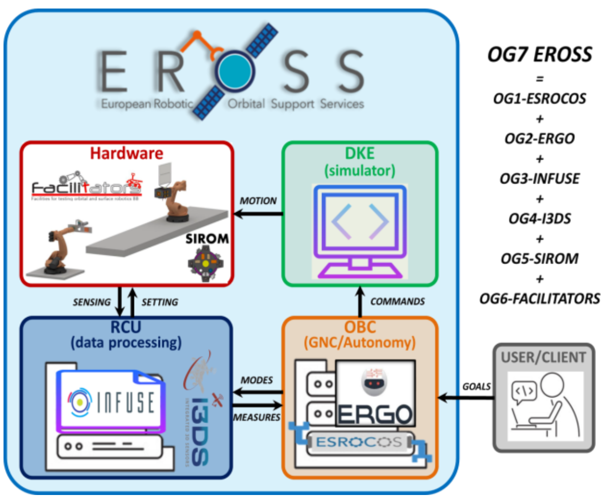


Figure 30 - EROSS closed-loop merging the six initial H2020 OGs in the SRC of Space Robotics

7.1. Platform-Art Rendezvous Test Bench

The test bench used for this demonstration is the **platform-art©** robotic test bench developed by GMV in Madrid (Spain).It allows supporting the verification and validation of the Guidance, Navigation and Control (GNC) systems for short range phases of rendezvous, formation flying, servicing and debris removal missions.

The hardware architecture of the dynamic test bench is composed by:

- **Avionics** (Real-time PIL test bench components, bottom part of the figure). Real time PIL test bench, where the stimulation to optical/laser sensors and real dynamic recreation is directly provided by the moving platform facility elements and the use of realistically manufactured mock-ups.
- **Mechatronics** (Motion Facility, upper part of the figure). Robotic motion facility, which has been built taken into account like the presence of heterogeneous HW together with the need for executing a chain of hierarchical tasks, including :
    - The **Motion Control System** controlling the execution inside the test bench, receiving the kinematics information from the Real World simulator and processing it to move the robotic systems in a synchronous, safe and accurate manner.
    - The **2x KUKA KR C2 robots**. Each robot controller receive its motion solution from the Motion Control System and execute the motion command.
- The **illumination control system**. It includes a sun-representative lamp hosted on a long-range (16 meters) 6-Degrees of Freedom Cartesian system. It receives its motion solution from the Motion Control System.
- The **UR-10 Robotic 6DOF manipulator**. This robot has been used in EROSS project to mimic the behaviour of the Servicer robotic arm embedded on its platform. Due to mass constraint it was accommodated on one of the KUKA robot to ensure that the inertia reached during the capture were not exceeding the KUKA limits.

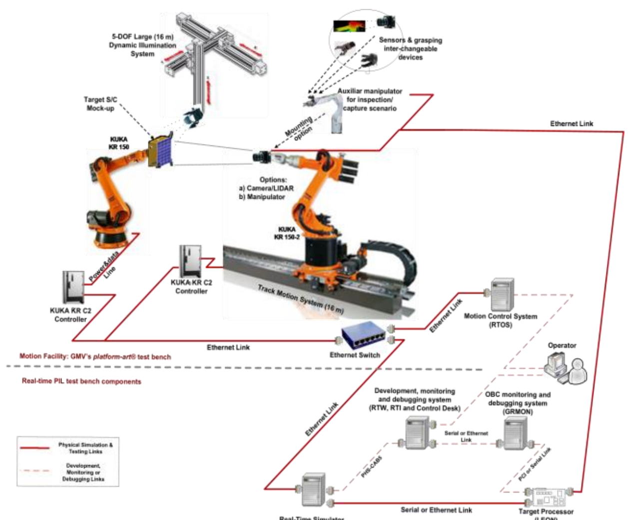


Figure 31 – Platform-art© kinematic test bench architecture (example with a PIL/LEON configuration]

7.2. Closed-Loop Test Overview

The following sections provides only an overview of these closed-loop results **focusing mainly on the long-range section of the overall Validation Approach** introduced in Section 4.

With this respect, the closed-loop test followed a two-step approach with open loop acquisitions to characterize the GNC functional chain behaviour and performance on the test bench before closing the loop. The following results illustrates both the open and closed loop results with the navigation chain characterization, and the closed-loop performance in both the nominal and contingency scenarios.

The first nominal test perform the complete approach until the berthing position using the visual navigation feedback to align properly the Servicer platform with the Client one.

The second contingency test was performed to validate the autonomy layer of the ERGO agent in case of system failure. During this scenario, a camera failure was simulated and the system autonomously took the decision to move back to the last safe station keeping point, triggering internally the proper GNC modes and updating the guidance reference accordingly.

7.3. Open-Loop Characterization

Hereunder some examples of the 3D model re-projection is given for the different Image Processing solution and Visual Navigation chain available in the EROSS project, namely: the INFUSE processing solution (i.e., software solution) with a model-based approach at long range and a marker-based approach at close range, and the ARAMIS sensor (i.e., both hardware and software) used in both visible and thermal spectrum valid for both long and short ranges.

These data processing are then filtered at GNC level to fused the data and propagate the signals over time, making the Navigation chain more robust to the potential loss of tracking when bad illumination conditions occur.

Figure 32 – 3D model re-projection on the Visual Camera image running the INFUSE processing solution at long range

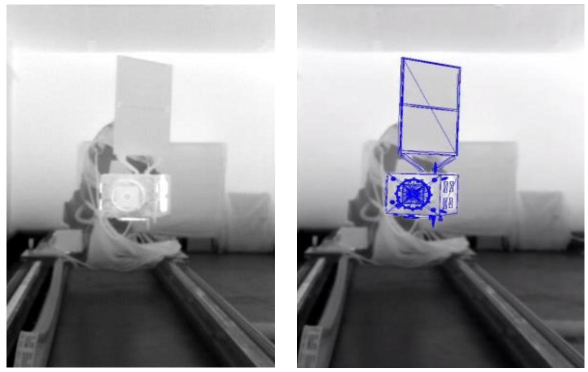


Figure 33 – 3D re-projection on the Thermal Camera image running the ARAMIS processing solution at long range

Figure 34 – Marker Tracking using the Visual Camera image running the INFUSE processing solution at short range

7.4. Nominal Closed-Loop Results

As mentioned earlier, this test focuses on the Long-Range section of the overall EROSS demonstration. It begins with the two spacecraft separated by 30m at mission level (i.e., 10m on the test bench), with the servicer maintaining the relative distance in Station Keeping Mode.

The demonstration ends with the servicer spacecraft in the final station keeping position at 3m (i.e, 1m in the demonstration facility considering the scale factor).

The following table presents the flight plan prepared for the nominal scenario:

Table 3 - Flight plan of the nominal scenario

Time	Flight plan	Expected behaviour
<100s	Standard initialization at Hold Point SK3A (30m)	Servicer is stable in attitude and trajectory
100s	Send command of Straight Line motion with Hold Point to SK3B (10m)	GNC Mode transition. New hold point at SK3B.
<1200s		Automatic transition to station keeping mode when the hold point is reached
1200s	Send command of Straight Line motion with Hold Point to SK4 (3m)	GNC Mode transition. New hold point at SK4.
<2000s		Automatic transition to station keeping mode when the hold point is reached

This flight plan is commanded by an operator that emulates the role of the control centre in a real space mission. Different protections are implemented at ERGO and GNC level to accept the tele-commands only when the current GNC context allow for it. This was specified through the decision trees, implemented in the autonomy framework and validated in the Software-in-the-Loop (SIL) perimeter.

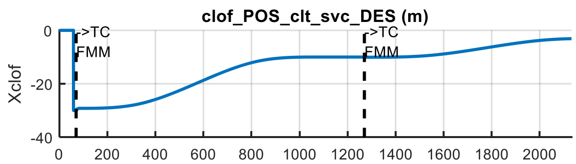


Figure 35 – On-board Guidance profile for the Nominal scenario

Along this experiment, the main goal was to demonstrate the coherent and robust behaviour of the closed-loop with all the previous building blocks of the previous Calls of the SRC in Space Robotics illustrated in Figure 30. In order to track safely and accurately the reference profile given by the guidance, the whole HW & SW loop is used in this EROSS experiment to be as close as possible from the final Servicer architecture and to raise the Technology Readiness Level (TRL) of the overall solution for future servicing missions.

The following performance figures were achieved based on the telemetries and ground truth measurement taken from the GNC application during the demonstration. An overall correct behaviour is observed, with the GNC of the servicer generating autonomously a guidance profile and maintaining low control error during the approach manoeuvres. **A requirement of 1% of relative positioning error was required and has been achieved** in this experiment thanks to the fine tuning of the whole GNC loop.

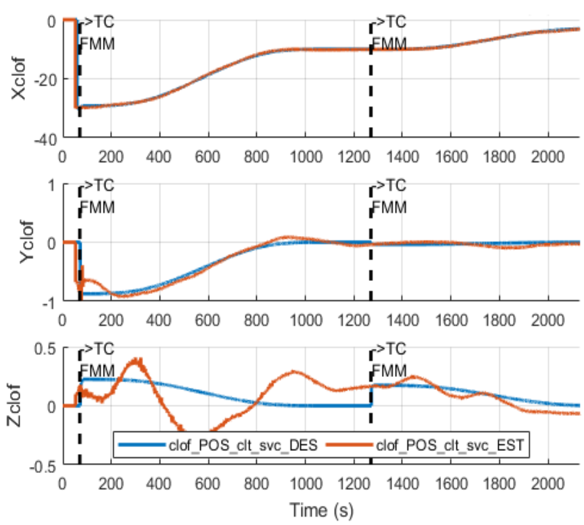


Figure 36 – Desired VS on-board estimate of the relative position of Servicer wrt Client for the ***nominal approach***

7.5. Contingency Closed-Loop Results

The same test setup was performed for the contingency scenario. The flight plan is identical to the nominal one in terms of orbital configuration and sensors/actuators selection, but during the first approach manoeuvre an error is introduced to check the autonomous triggering of the transition to an Escape mode activating the collision avoidance manoeuvre.

In the following image, the graphs in position illustrates the so-called "rebound" of the Client vehicle from the Servicer perspective as the orbital manoeuver is performed to escape from the Client. This rebound is generated by the high impulse manoeuver and the orbital mechanics coupling between the X and Z axis of the Local Orbital Frame axes [12].

A second comment to be drawn from these results is that the Servicer perfectly recovered from the failure by reaching autonomously the last safe station keeping point to wait for the ground feedback and next GO/NOGO command. This demonstrates the right behaviour of the ERGO agent to monitor the GNC architecture and trigger the right modes in emergency.

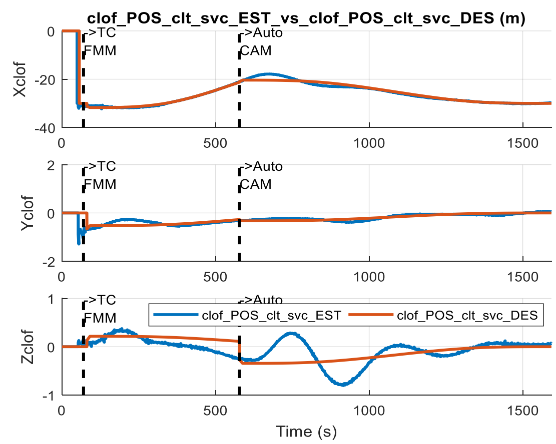


Figure 37 – Desired VS on-board estimate of the relative position of Servicer wrt Client for the ***contingency approach***

8. Conclusion

As a summary, the ground experiments of the EROSS project have been presented in this paper. They ranged from unitary and cross-checks to integrate the system-level demonstrator of the Servicer and Client vehicles. These tests validated the EROSS architecture with dynamic and kinematic tests in representative environments.

It has been the first time that the feasibility and performance of a system architecture merging all the European Building Blocks from the past H2020 OGs was demonstrated in closed-loop.

The next step of this demonstration is now the on-going OG12-EROSS+ project led by Thales Alenia Space to mature the system architecture towards the first European demonstration of an On-Orbit Servicing system by 2025.

Acknowledgements

Thales Alenia Space would like to sincerely thank the European Commission who made possible such project. EROSS project was co-funded by European Union's Horizon 2020 research and innovation program under grant agreement N°821904 was part of the Strategic Research Cluster on Space Robotics Technologies as Operational Grant n°7.

In addition, Thales Alenia Space would like to thank and recognize the support of all his core partners: GMV, SINTEF AS, National Technical University of Athens (NTUA), PIAP Space, SENER, SODERN, and Space Application Services.

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