EROSS+ GROUND DEMONSTRATION FROM NUMERICAL MODEL TO HARDWARE IN THE LOOP VALIDATION

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ABSTRACT

This paper introduces the tuning and validation process followed to increase the maturity of a Guidance, Navigation and Control software fed by an Image Processing software processing cameras images during an orbital rendezvous scenario. This validation process and the resulting experiments were conducted during the EROSS+ project, for which a mission and system design review are proposed before describing into more details the validation results. They are based on the Model/Software/Processor/Hardware-in-the-Loop approaches, led sequentially and iteratively to converge the On-Board Software tuning towards the flight hardware configuration and characteristics, like the impact of processing delays, numerical errors, or high uncertainty. Eventually, the performances of both the Image Processing and the Guidance, Navigation and Control are illustrated on a Hardware-in-the-Loop experiments simulating a Vbar approach of the Servicer vehicle towards a Client. Analyses and recommendations are made on the validation process followed and on its potential improvements to increase the software development and validation along with the measurement chain characterisation for performance model derivation.

1 INTRODUCTION

Access to space is becoming more and more affordable, making on-orbit servicing closer to market than even. Thanks to new technologies and New Space actors, disruptive missions and services are being set up to the benefit of end-users. However, the subsequent increased use of space (especially with mega-constellations) also highlights the need of a more sustainable vision for the future infrastructures. It is not possible anymore to design and launch disposable spacecraft without considering the consequences, and On-Orbit Servicing (OOS) is a first step towards a change of paradigm: the same technologies, typically autonomous rendezvous, refuelling, Orbital Replaceable Unit (ORU) exchange, repair and waste management with robotic tools, will be used in future smart, flexible and modular spacecraft [1-2].

Designing the right mission to enable a go-to-market for future OOS missions is the main goal for the EROSS+ project, and now of the EROSS IOD mission led by Thales Alenia Space. It focuses on the short-term demonstration of the key capabilities like coordinated close rendezvous between two free flying spacecraft (a first in Europe) and robotic operations such as capture, refuelling and change of payload with multi-body dynamics [13-16]. EROSS+ showcases a mission design that will provide both life extension and life enhancement to future space systems, therefore answering both short-term customer needs and anticipating future new business perspectives.

The final aim of the H2020 EROSS+ project was to prepare and carry out the last maturation & manufacturing steps to make this dream product true with the now on-going EROSS IOD project to fly a pioneering mission by 2026 in the scope of the Horizon Europe funding. With a strong customer-driven approach, the proposed demonstration will enable access to the following market segments:

- In the short term, On-Orbit Servicing for unprepared clients: Inspection/surveillance, life extension (via station keeping, attitude and orbit control being taken over by the Servicer), change of orbit and end-of-life removal.
- In the mid-term, On-Orbit Servicing for prepared clients: life extension by refuelling (thus avoiding immobilisation of a servicer for several years), upgrade and potentially repair. This is where the proposed demonstration will position Europe in a leading position, as this requires a unique robotic dexterity and autonomy, as well as specific design features of the Client spacecraft soon to be standardized according to institutions roadmaps.
- In the long term, In-Orbit Assembly and Manufacturing: the technologies developed and showcased will enable building blocks to prepare the change of paradigm in how the space infrastructures will be designed, produced and exploited in a more sustainable way.

From a Guidance, Navigation and Control (GNC) standpoint, these applications and missions require similar functions for moving safely around another object in space despite the internal and external disturbances, and the orbital mechanics constraints. With that respect, Thales Alenia Space has lead four Horizon 2020 projects with the European Commission over the last 7 years to mature the related GNC and robotics technologies from the sensor to the on-board software and to the ground link. This paper aims at introducing the validation approach followed by the company and its partners to cover a complete vision-based GNC solution for OOS by using the different validation means available from Model-in-the-Loop (MIL), to Software-in-the-Loop (SIL), including Processor-in-the-Loop (PIL), and eventually to Hardware-in-the-Loop (HIL).

In the scope of the EROSS+ project, a complete experimental ground setup has been used to validate the short-range rendezvous with a spacecraft including the management of contingencies and the robustness to harsh illumination conditions. The ground architecture was focused around the sensors connected to a prototype of the Servicing Control Unit (SCU), and coupled with a GNC software running on a prototype of an On-Board Computer (OBC). Three main test beds have been used to validate (a) the vision-based navigation approach in closed-loop on GMV's Platform-Art robotic bench; (b) the robotic controller compliance during the capture and contact on DLR's CAESAR robotic bench with a 0-gravity compensation system; (c) the avionics integration and the autonomy loop on Thales Alenia Space's ROBY robotic test bench.

This paper will focus though on the first mission step with the safe approach of a Client spacecraft using relative sensors feeding an autonomous GNC software coupled with an advanced image processing. Firstly an overview of the project is given in Section 2 to introduce the overall project context, the mission scenario, and the system design with the sensor selection approach. Then a second part described how the end-to-end validation of such a functional chain has been set up by following a step-by-step approach in Section 3 fusing the previously mentioned MIL, SIL, PIL and HIL methods to incrementally increase the overall Technology Readiness Level (TRL) of the solution with a flexible process depending on available time & effort & means at each stage. Eventually the Section 4 is devoted to the results obtained for both the validation of the Image Processing software and for the GNC autocoded software with numerical and experimental tests [16]. A final conclusion is given to close the paper with the key recommendations on the validation approach followed and on its potential risks/opportunities in the scope of a future mission.

EROSS+ project has been co-funded by European Union's Horizon 2020 research and innovation program under grant agreement N°101004346 and is part of the Strategic Research Cluster on Space Robotics Technologies as Operational Grant n°12. Thales Alenia Space has led this project in collaboration with DLR, GMV, SINTEF AS, and PIAP Space.

2 CONTEXT

2.1 EROSS+ Project

The project “EROSS+ Phase A/B1” standing for “European Robotic Orbital Support Services” has been led over 2021-2023 to mature the future robotic servicing missions with a highly-autonomous and coupled Guidance, Navigation and Control (GNC) architecture for both a satellite platform and its embedded robotic arm. This project is built upon the previous developments of the Operational Grants led by the Strategic Research Cluster in Space Robotics funded by the European Commission since 2016 as part of the “Horizon 20202” (H2020) funding framework [3-12].

More specifically, EROSS+ project aims at deriving a system design of a robotic Servicer approaching, capturing and servicing a Client satellite. It thus integrates and demonstrates the key European robotic building blocks by demonstrating their performances from Model in the Loop (MIL) tests to Hardware in the Loop (HIL) experiments. The next stage of the EROSS+ project is now engaged with the EROSS IOD program funded by the European Commission under the “Horizon Europe” funding framework since February 2023, and targeting a launch of the mission of demonstration by 2026 for which Thales Alenia Space in France is the project coordinator.

2.2 Mission Scenario

The main use-case of EROSS+ project is to demonstrate the capability of a Servicer spacecraft to perform medium and close-range rendezvous, before capturing and manipulating a Client satellite with a high degree of autonomy. The Client satellite is considered “collaborative” and “prepared” for servicing operations such as refuelling and payload replacement. Four main steps are foreseen with:

- the approach with an autonomous visual-based navigation using advanced processing and filtering techniques, along with on-board guidance functions to derive the safest relative path to follow;
- the capture using state-of-the-art compliance control techniques to synchronize the robotic arm and its platform;
- the mating of the two spacecraft through a dedicated interface for berthing;
- the robotic exchange of a replacement payload designed with standard interfaces.

An illustration of the different steps is given below from the Client standpoint. The Client is assumed to be actively controlled in attitude only, while remaining on a given servicing orbit: this reference orbit defines a Local Orbital Frame (LOF) linked to the centre-of-mas of the Client in which the Servicer relative motion is planned and executed thanks to its GNC and vision subsystems.

The EROSS+ scenario is assumed to start once the inertial phases have been performed to reach the Client orbit, and when the Servicer GNC is switching from inertial to relative navigation as part of the Homing phase. It thus covers the Closing phase to perform impulsive manoeuvers towards the Client, and the Forced Motion & Capture phase performed by continuous manoeuvres to maintain the vehicles safety and integrity during this risky phases.

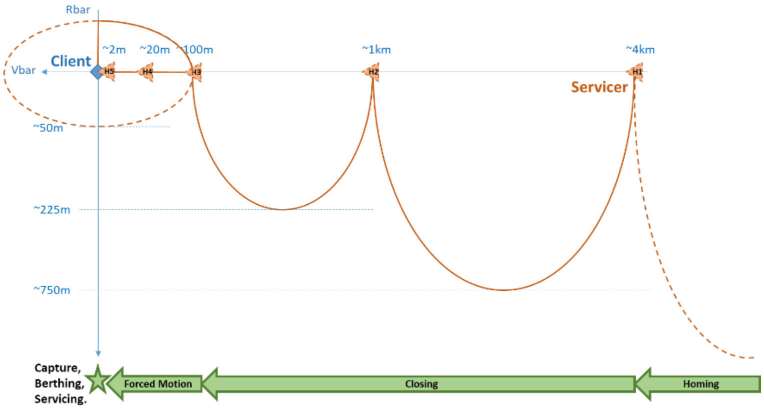


Figure 1: Illustration of the EROSS+ mission in the Client Local Orbital Frame (C-LOF)

2.3 System Overview

An illustration of the Servicer and Client spacecraft is provided here in the configuration of the approach and inspection phase running as part of the Forced Motion phase. The Fields-of-View (Fov) of the different relative sensors considered are also included to visualize how the Client tracking from far to close range is also imposing a careful selection of the sensors list.

In the scope of the EROSS+ project, the complete design of the Servicer and Client has been performed as part of the Phase A/B1 of the project, while a separate track has been followed to feed a technological validation of the Rendezvous operations covering the Closing and Forced Motion, and the Robotic operations covering the Capture and Servicing.

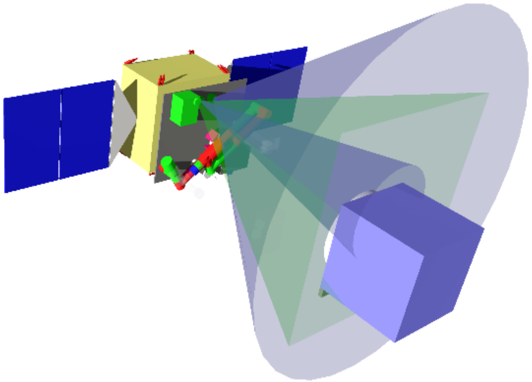


Figure 2: EROSS+ mission configuration during the approach and inspection

With this respect, a sensor selection and preliminary sizing has been led to select to the relative sensors main characteristics based on their combination during the mission phases, as follows: (1) a delta-GNSS approach is used for long range to fuse the GNSS data coming from both the Servicer and the Client (based on Ground link sporadic inputs), (2) a Narrow Angle Camera (NAC) is used to detect the Client at long range and perform the Closing phase with at least a relative position estimation, (3) a Wide Angle Camera (WAC) is used at shorter range for the inspection and the forced motion phases to provide a relative position and attitude of the Client, (4) a Robotic WAC camera is used for the capture and servicing phases with a very wide angle optics, and (5) a LIDAR system is considered as a safe and robust redundancy of the nominal vision-based navigation chain in the scope of the EROSS+ mission. This latter approach will allow to gather flight data on the GNC performances when coupled with vision-only or with LIDAR-only, and then to draw the key drivers for later system design of commercial applications.

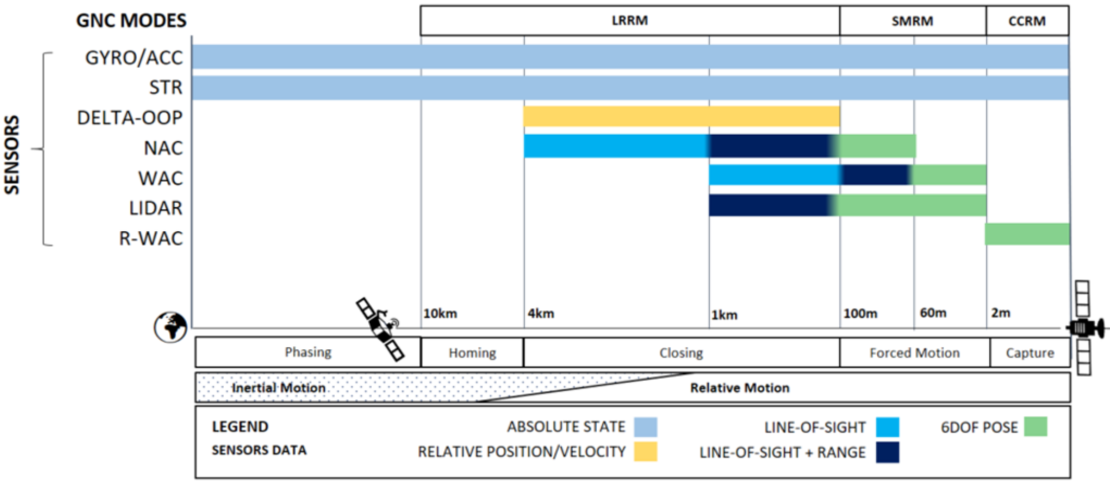


Figure 3: Relative sensors selection and sizing to detect and track the Client vehicle

More specifically in the scope of the Rendezvous validation presented in this paper, the key elements of the Servicer design are part of the Avionics subsystem, including both Hardware (HW) and Software (HW) elements. Regarding the Client vehicle, only a HW mock-up has been used for the experiments while a complete vehicle design has also been derived in the course of the phase A/B1.

Servicer HW (SVC-HW):

- Processing Boards: On-Board Computer (OBC) and Servicing Control Unit (SCU).
  They represent the different processing units where SVC-SW elements are running.
- Sensors: Servicer Illumination System (S-ILL), Servicer Narrow Angle Camera (S-NAC) and Servicer Wide Angle Camera (S-WAC). They represent the rendezvous sensors in charge of acquiring the images to be processed by the Image Processing SW element, called "RDV_IP".
- Servicer structure: mechanical structure of the Servicer vehicle, on which the rendezvous sensors equipment are accommodated. They are all merged on a single physical panel of the Servicer platform to be aligned towards the Client vehicle.

Servicer SW (SVC-SW):

- Platform related SW: Mission and Vehicle Management (MVM), Rendezvous Guidance Navigation and Control (RDV_GNC) as part of the On-Board SW (OBSW).
  They represent the SW in charge of implementing the different vehicle and GNC modes applicable to rendezvous operations. These SW elements are running in the OBC HW element.
- Payload related SW: RSM and RDV_IP: they represent the SW in charge of implementing the SW autonomy and image processing functionality to support the rendezvous operations. These SW elements are running in the SCU HW element.
- CAM_EQ_IF: it represents the SW element in charge of interfacing with the cameras (SNAC and SWAC) to enable them and to retrieve the image to be provided to RDV_IP SW element. This SW element is running in the RCU HW element.

Client HW (CLT-HW): representative mock-up of the Client S/C to support the Rendezvous Experiments, including a representative external shape from the visual point of view (flight materials) and including the specific features used to support the rendezvous and ease the image processing by the Servicer for the "prepared" scenario.
As one can notice, the LIDAR equipment was not used during the EROSS+ experiment presented in this paper, which were in closed-loop, but it has been tested separately in open-loop during a test campaign in Thales Alenia Space on the ROBY robotic test bench in February 2023. These results were based on a prototype developed by SINTEF and will be presented in a future paper in the course of EROSS IOD program.

3 VALIDATION APPROACH

The core elements of this paper is the review of the process and results of the incremental validation proposed from the technology level until the end-to-end experiments. The advantage of this approach is its inherent modularity allowing to update and re-validate some key elements of Guidance, Navigation and Control (GNC) or Image Processing (IP) software with unitary & cross-checks based on automated tools in order to minimize the delay to steer towards HIL test. This automated testing process includes SIL & PIL testing framework coordinating the engineering teams in GNC and SW using a now established autocoding and compilation tool chains in Thales Alenia Space.

The current section aims at reviewing into more details this validation approach, the bench architecture used to reach such a tool chain, the means available for this project, and eventually the technical activities actually possible to lead within the scope of the EROSS phase A/B1.

3.1 Overall Approach

Considering the context of On-Orbit Servicing, a strong challenge is to integrate large parts of the Servicer vehicle with new technologies at HW and SW levels, and not only at the payload stage but also reviewing the platform design. Considering that EROSS+ was still a Research & Development study, the HW cost of Engineering or Flight Models (EM / FM) was not affordable hence ground Components-of-the-Shelf (COTS) were procured for the cameras used during the experiments. This latter means that the maturation process was focused on the SW validation, and more specifically for the GNC and the IP.

When starting EROSS+, the overall chain's Technology Readiness Level (TRL) of the different software building blocks of GNC or image processing were at a prototype stage of TRL3/4, running on ground processing units (e.g., laptop) with ground operating systems (e.g., Linux). The four steps approach illustrated below is the incremental validation to move from TRL3/4 to TRL5 by implementing tests with Model-in-the-Loop (MIL), then Software-in-the-Loop (SIL), to Processor-in-the-Loop (PIL), before performing Hardware-in-the-Loop (HIL) experiments. The last TRL level after PIL or HIL testing is open to debate as it depends widely on the operating system used on the board, flight-qualified or not, on the low-level drivers for the hardware/software interfaces, and on the time scheduling and partitioning of the different components of the complete On-Board Software (OBSW) running along the tested SW component. It can thus vary from TRL5 to TRL6-7 based on this architecture. For the EROSS+ R&D project, only TRL5 can be claimed as only the GNC or IP components were tested in a relevant Operating System but not interfaced with the flight hardware and not interface with the final OBSW components.

This last HIL step is often qualified as "end-to-end" in the sense that it merges the key software hosted in a representative processing boards and running in a representative robotic test bench creating realistic datasets from the relative sensors. In the scope of EROSS+, the preparatory work for MIL and SIL tests has been performed at Thales Alenia Space on the Software Verification Facility (SVF), while part of the HIL test was derisked on the ROBY robotic test bench. Then the final end-to-end HIL test was performed at GMV on the Platform-Art© robotic test bench to characterize the Rendezvous phase of the mission. As a recall, another HIL test campaign occurred at DLR on the CAESAR robotic test bench to test the Robotic Capture and Servicing phases of the mission.

Over the complete process of SW validation, the following V-cycle combined with internal loops has been used during the EROSS+ project, as part of the overall approach established in Thales Alenia Space.

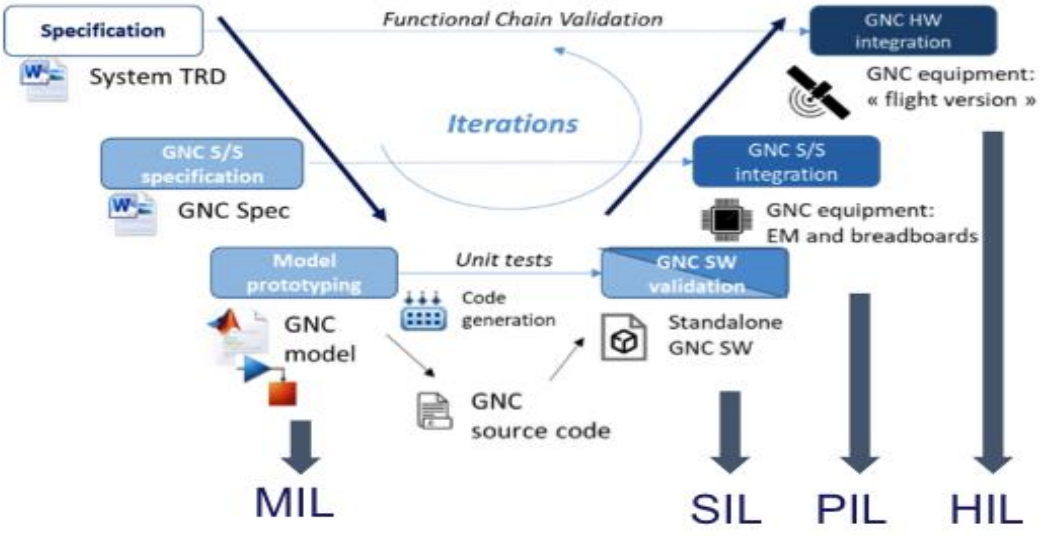
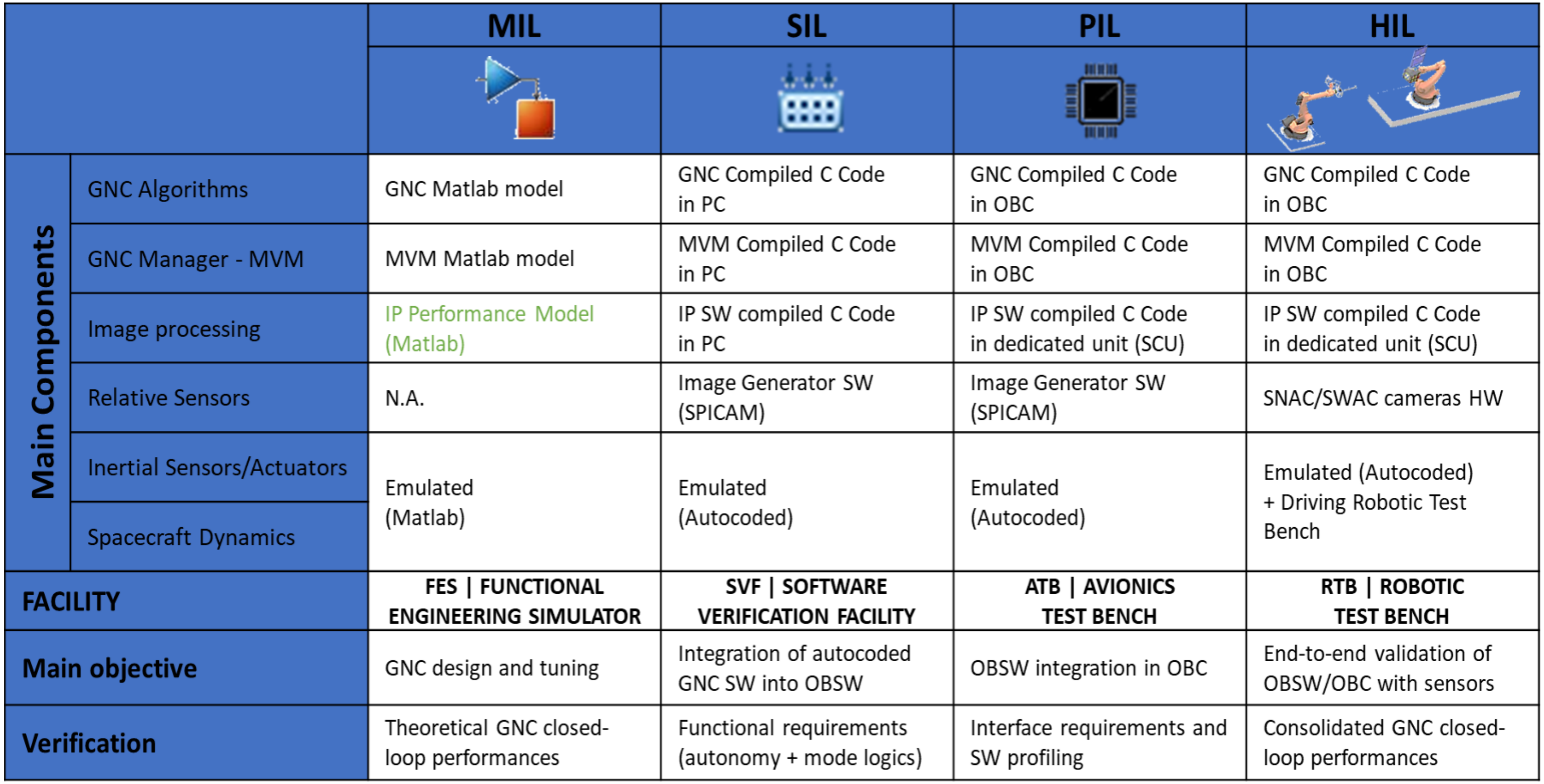


Figure 4 - Incremental On-Board Software validation by MIL-> SIL -> PIL -> HIL

Figure 5 : Overview of the MIL > SIL > PIL > HIL process of validation with the related means and goals



		MIL	SIL	PIL	HIL
Main Components	GNC Algorithms	GNC Matlab model	GNC Compiled C Code in PC	GNC Compiled C Code in OBC	GNC Compiled C Code in OBC
	GNC Manager - MVM	MVM Matlab model	MVM Compiled C Code in PC	MVM Compiled C Code in OBC	MVM Compiled C Code in OBC
	Image processing	IP Performance Model (Matlab)	IP SW compiled C Code in PC	IP SW compiled C Code in dedicated unit (SCU)	IP SW compiled C Code in dedicated unit (SCU)
	Relative Sensors	N.A.	Image Generator SW (SPICAM)	Image Generator SW (SPICAM)	SNAC/SWAC cameras HW
	Inertial Sensors/Actuators	Emulated (Matlab)	Emulated (Autocoded)	Emulated (Autocoded)	Emulated (Autocoded) + Driving Robotic Test Bench
	Spacecraft Dynamics				
FACILITY		**FES | FUNCTIONAL ENGINEERING SIMULATOR**	**SVF | SOFTWARE VERIFICATION FACILITY**	**ATB | AVIONICS TEST BENCH**	**RTB | ROBOTIC TEST BENCH**
Main objective		GNC design and tuning	Integration of autocoded GNC SW into OBSW	OBSW integration in OBC	End-to-end validation of OBSW/OBC with sensors
Verification		Theoretical GNC closed-loop performances	Functional requirements (autonomy + mode logics)	Interface requirements and SW profiling	Consolidated GNC closed-loop performances

The Mission requirements turns into a Technical Requirements Document (TRD) at System level which serves as based to derive the GNC subsystem (S/S) Specifications. Based on this, the GNC algorithms are implemented and tested against a Dynamics, Kinematics, Environment (DKE) simulator in the scope of the MIL tests on Matlab mainly. At technical level in EROSS+, Thales Alenia Space was in charge of the "GNC Manager" function called Mission & Vehicle Management (MVM), along with the Navigation filter and the Control design. The Guidance algorithms were developed by GMV, and then integrated by Thales Alenia Space in the MIL framework to generate code of the complete GNC perimeter. In addition, GMV was also in charge of the Image Processing SW which was directly coded in C.

At the bottom of this V-cycle, the autocoding tool chain then allows to generate the C code of the GNC software in order to test it for the Software-in-the-Loop (SIL) test on a Linux Operating System first. This test allows to check the non-regression between the MIL framework and the SIL one, called Software Verification Facility (SVF). This framework contains all the necessary tools to interface an autocoded GNC solution with an environment software running the DKE in real-time with the proper time-synchronisation between their execution.

Then the Processor-in-the-Loop testing was meant to progress on software maturation by using a representative flight Operating System (OS) with PikeOS. This PIL test was prepared on Thales Alenia Space and GMV sides to implement the GNC and the IP closer to the future flight version.

Eventually, the HIL test was initially meant to couple the integrated GNC and IP SW, while coupling them with the COTS camera hardware looking at a Client vehicle mock-up on a robotic test bench driven by the DKE environment. Unfortunately, the progresses in PIL tests were more challenging than expecting and were conducted in a parallel branch, meaning that the PIL results were not used in HIL, but rather the SIL outcomes .in a non-flight OS. These latter were directly coupled with the COTS cameras and the robotic test bench to perform the closed-loop tests.

3.2 Validation Architecture

To support the previous validation approach, the EROSS+ project has been based on the following product tree during the HIL experiments demonstrating the Rendezvous phase of the mission. The core elements described in the MIL to HIL testing are highlighted in red below, and they are the core components for which results are presented in the next section. This product tree is based on a subset of the overall product tree of the Servicer and Client vehicle introduced in Section 2.3.

Two main elements differentiates from the System Product Tree as the mechanical structure were replaced by mock-ups to support the experiments at R&D level: 1x Servicer mechanical mock-up to mount the cameras and the illumination device, and 1x Client visual mock-up including a representative external shape from the visual point of view (flight materials) and including the specific features used to support the rendezvous and ease the image processing by the Servicer for the "prepared" scenario (i.e., markers or other).

Eventually, testing components have been added including the Robotic Test Bench used to conduct the Rendezvous Experiments, mainly at GMV on Platform-Art© and partially at Thales Alenia Space on ROBY; and the Electronics Ground Support Equipment (EGSE) hosting an emulation of the Servicer Control Centre (RDV_SCC) to take into account the TM/TC exchange during the Rendezvous phase, and the simulation of the rendezvous dynamics, kinematics and environment (RDV_DKE). This DKE element is also in charge of simulating Servicer sensors and actuators that are not part of the Visual Navigation Subsystem and needed to perform the rendezvous operations.

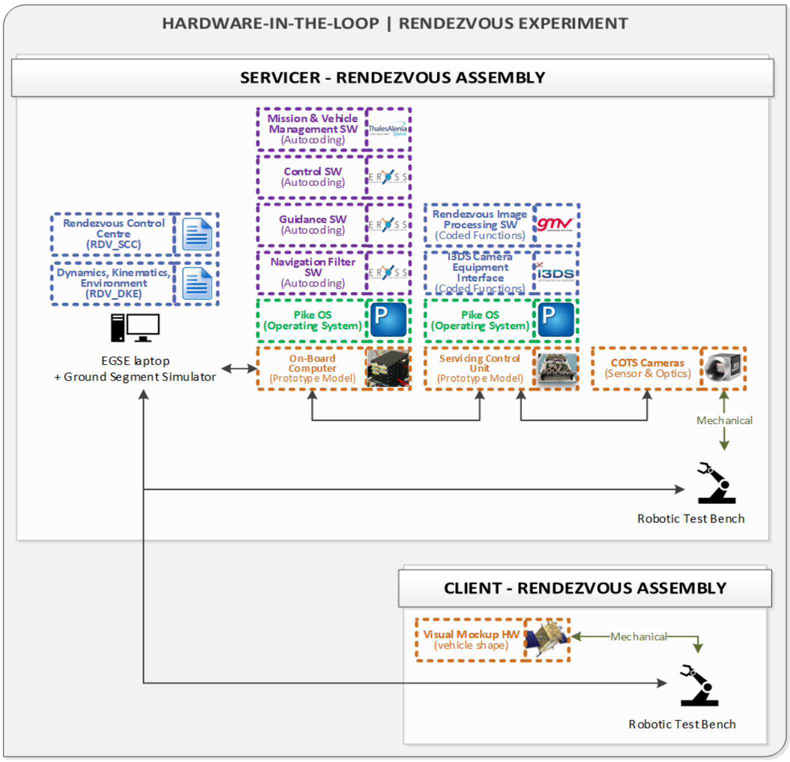


Figure 6 : Product Tree of the Rendezvous Experiment led during EROSS+

3.3 Validation Means

The previous equipment used during the EROSS+ project were partially reused from the EROSS project [14-15] regarding the Servicer and Client mock-up. The R&D rationale behind this choice was to minimize the time and effort dedicated in the development of test support components in order to focus the available means on the maturation of the SW components at stake, namely the GNC and IP SW porting within a representative flight Operating System.

The following schemes illustrate the design of the Servicer platform holding the relative sensors for the approach prior to the capture, and the Client spacecraft :

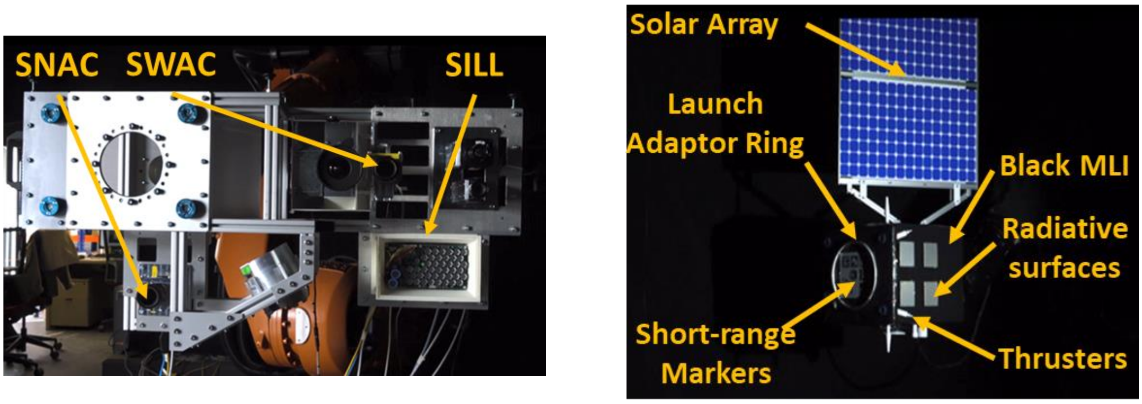


Figure 7 - Servicer and Client mockup used for the Rendezvous Experiments in EROSS+

Regarding the processing board, different units were used to represent the OBC hosting the GNC and MVM SW, and the SCU acting as a companion board hosting the IP SW. The OBC used for the PIL testing was based on a flight hardware with a PikeOS Operating System, while the SCU was inherited from EROSS project with a Zynq Ultrascale+ processor.

4 VALIDATION RESULTS

4.1 Test Logics

The GNC & IP validation were conducted closely according to the approach in Figure 5 :

1. Building a Performance Model of the IP based on a synthetic image generator (i.e., SPICAM tool developed by Thales Alenia Space) to characterize the performances of the measurement w.r.t. the relative distance to the Client, and to the illumination conditions;
2. Integrating the IP Performance Model into the FES simulator to design, tune and validation in MIL the GNC SW, and then autocode the GNC SW;
3. Performing the non-regression SIL experiments in the SVF with IP Performance Model;
4. Performing the extended SIL experiment with GNC and IP in the loop using synthetic images;
5. Performing the HIL experiment with GNC and IP coupled with the cameras HW.

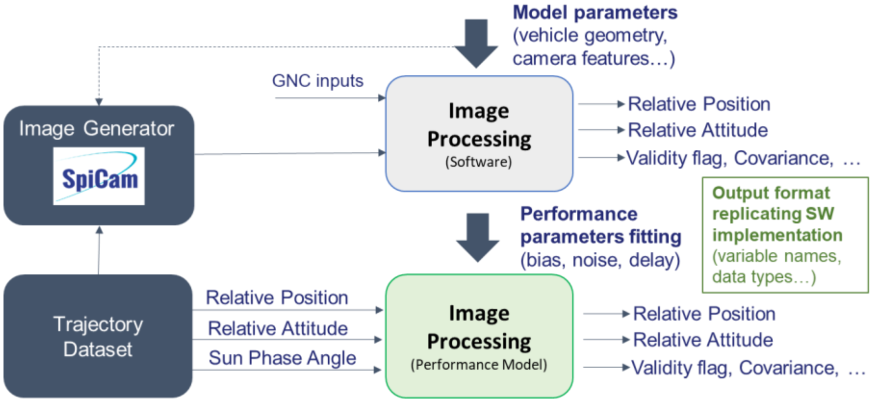


Figure 8 : IP Performance Model process

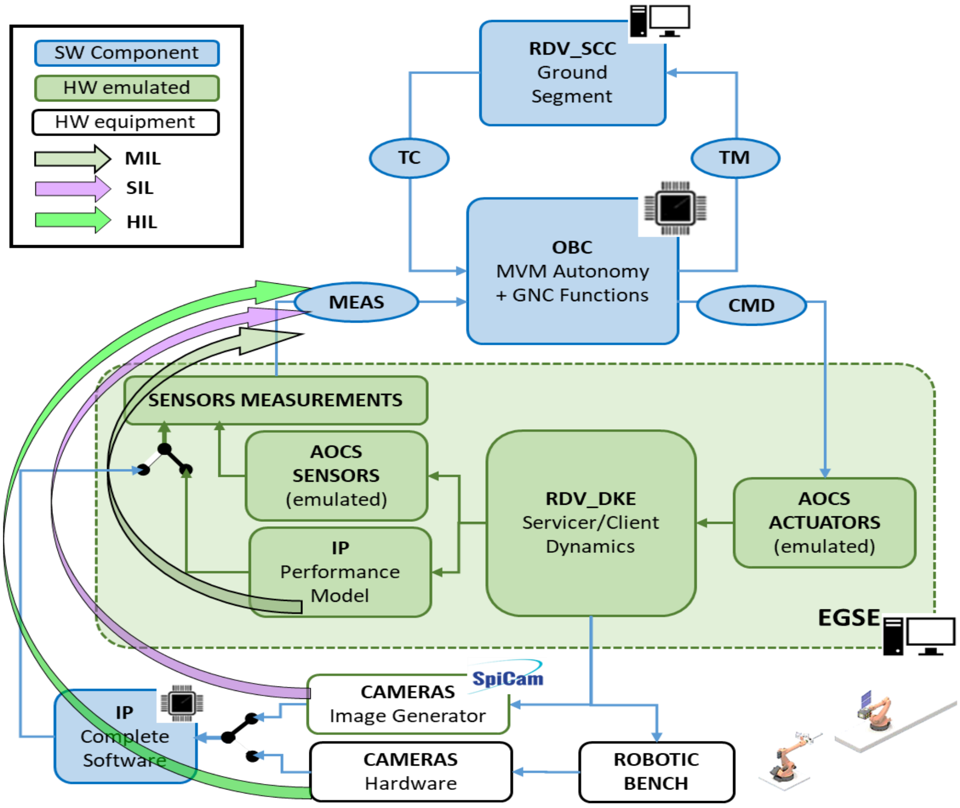


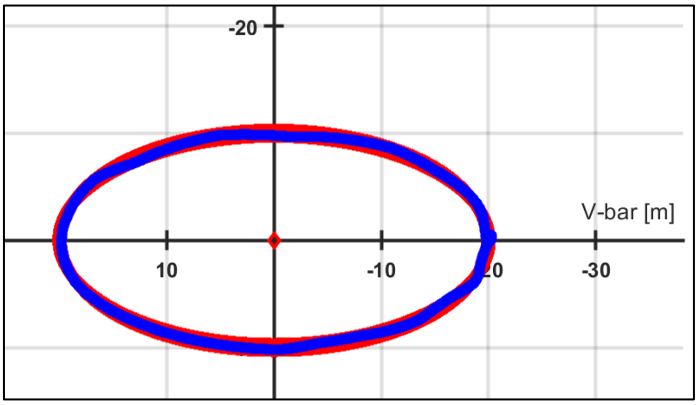
Figure 9 : Overall Architecture to switch from MIL to SIL to HIL tests

4.2 Test Scenarios

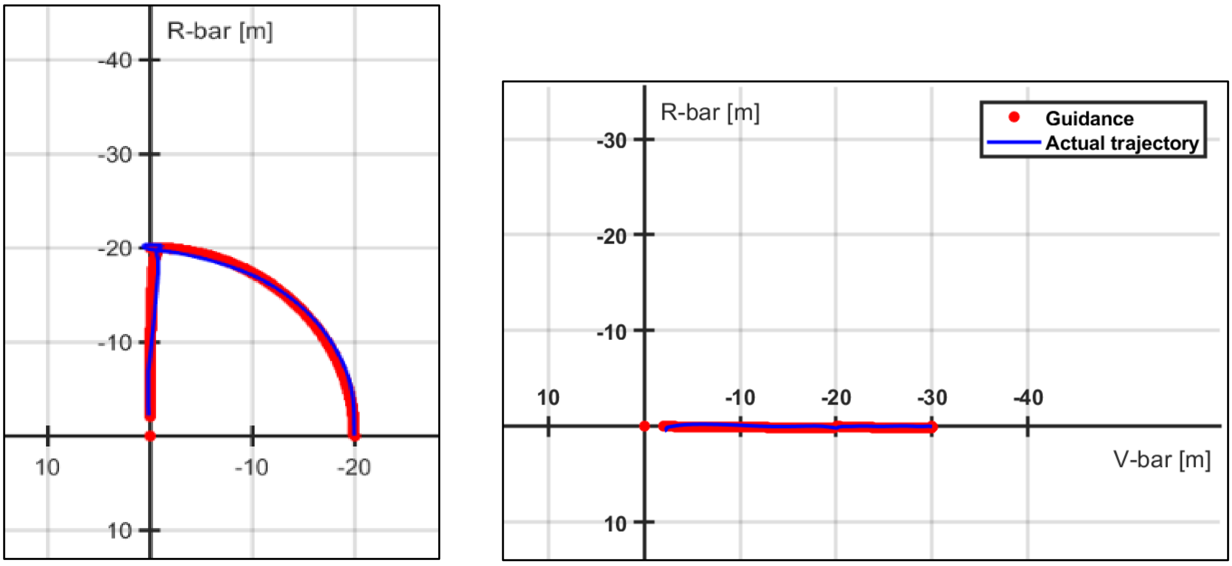
The GNC & IP validations have been performed on three main families of trajectories to check the robustness of the overall solution for different missions of rendezvous. These trajectories allow to vary (1) the sun phase angle to change the shadows and illumination conditions of the Client in the cameras field of view; the size of the Client vehicle in pixels in the images depending on the distance, along with the blurriness of the image as the Client is far from the distance of focus; and (3) to vary the speed of approach depending on the laws of orbital mechanics.

The following simulations were performed for three families of scenarios on the robotic test bench with Hardware In the Loop (HIL) :

- **TS0400** : A fly-around from Vbar axis to Rbar axis followed by a Rbar forced motion in straight line towards the Client (i.e., scenario for Telecom Geostationary spacecraft);
- **TS0600** : A forced motion along Vbar axis with two station keeping points before stopping close to the Client (i.e., scenario for Observation Low-Earth Orbit (LEO) spacecraft):
- **TS13000 :** An ellipse of inspection around the Client (i.e., for both GEO and LEO scenarios).



(a) Ellipse of Inspection



(b) R-bar approach

(c) V-bar approach

Figure 10: Profiles of the different testing trajectories for the Rendezvous Experiments

4.3 Image Processing results

This test consists of a forced motion approach along the V-bar axis, from -30 m to -20 m, a station-keeping in this hold point follows, and finally another forced motion approach along V-bar is executed until the servicer reaches -2m to the client SC to take over with the robotic arm operations. This scenario is simulated with a varying Sun direction that would be present during a V-bar approach to an Earth Observation Low-Earth-Orbit (LEO), meaning that the Sun axis is rotating along a cone defined by the orbit inclination and the time at which the rendezvous is performed along the orbit (i.e., phasing according to the true anomaly). Three experimental images are given below to illustrate the raw data to be processed by the IP at the beginning of the approach, at the hold point and at the final forced motion close to the Client vehicle.

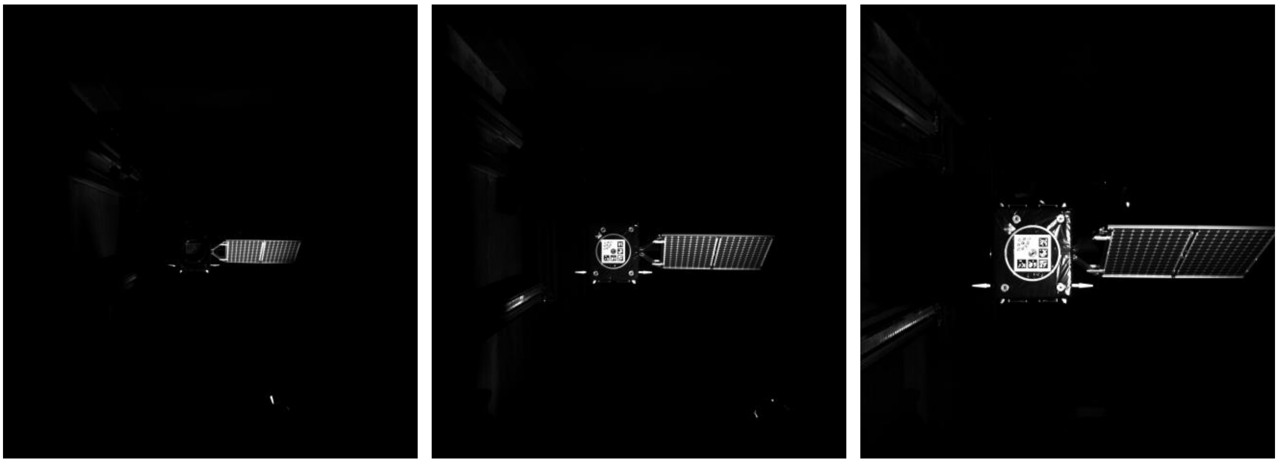


Figure 11 : Experimental images obtained with SWAC camera along TS0600 Vbar Approach

From the images it can be seen that the illumination conditions are too poor at the beginning of the scenario for the IP algorithm to run nominally. Furthermore, the primary direction in which the spacecraft moves is the Z CAM axis, in the depth direction of the camera, which for visual based navigation is a difficult direction to obtain accurate estimates (i.e., Z-axis of the camera is pointing towards the Client, along the camera line-of-sight).

The processing of these images provides the following results as output of the IP measurement feeding the Navigation filter, as part of the GNC SW.

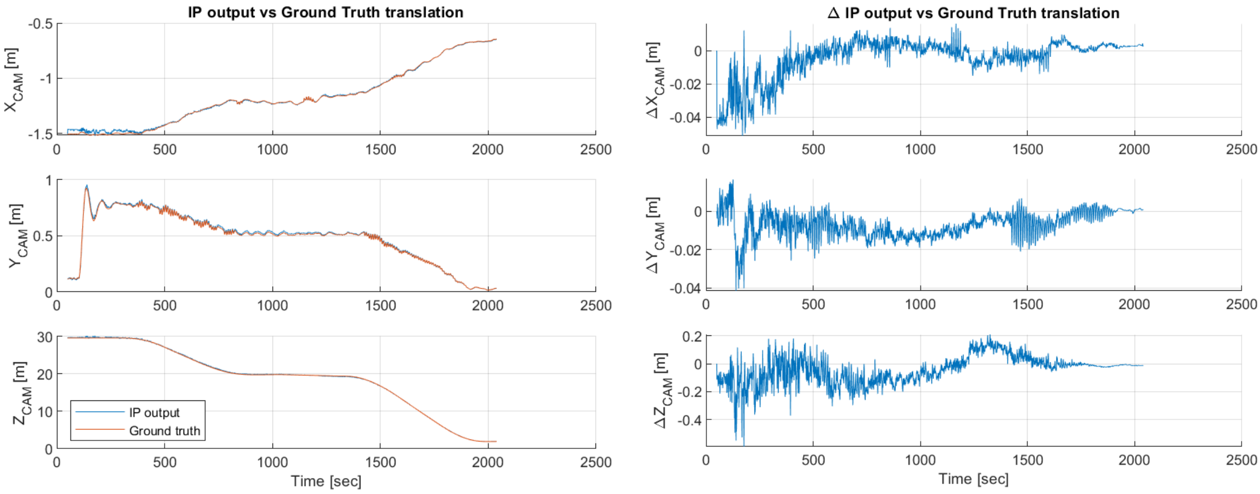


Figure 12 : IP Performance Analysis in relative Position on experimental dataset TS0600

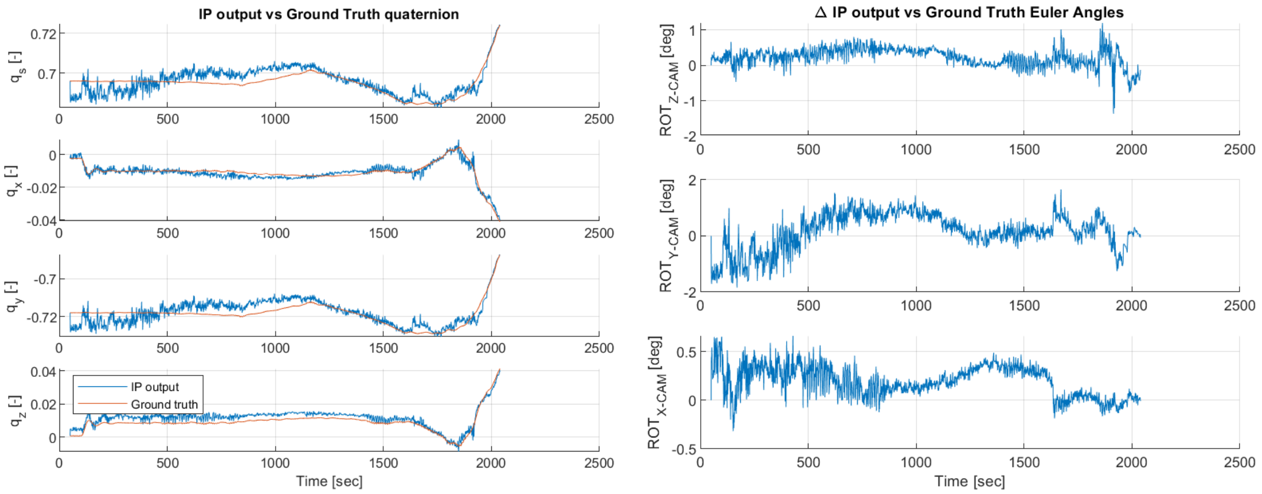


Figure 13 : IP Performance Analysis in relative Attitude on experimental dataset TS0600

From these previous figures, the following conclusions can be drawn:

- Since this scenario consists of two forced motion approaches in V-Bar, the closer the Servicer (and its cameras) is to the Client, the better pose estimation is provided by the IP (i.e. lower error between IP output and ground truth). This results confirms also the trend to a linear error with the relative distance, pending a similar lighting conditions overall;
- The attitude measurement reaches the expected performance level with an error below the degree on the three axes, and especially at distances smaller than 20m;
- The IP tracking is improved by the coupling with the Navigation filter as long as the filter is re-tuned on the experimental dataset, otherwise the error dynamics and the experimental latencies are too far from the initial Performance Model derived by the processing of synthetic images on a laptop. With the raw Navigation filter tuning from the GNC simulator, instability occurs and drives the system unstable over a few seconds/minutes;
- This latter conclusion recommends to refine the tuning of the whole GNC chain as the delays and error dynamics introduced in the loop during the experiments are not easily correlated with numerical models. An alternative is also to refine now the GNC models with the experimental characterization in order to improve the FES Simulator representativity for the later developments.

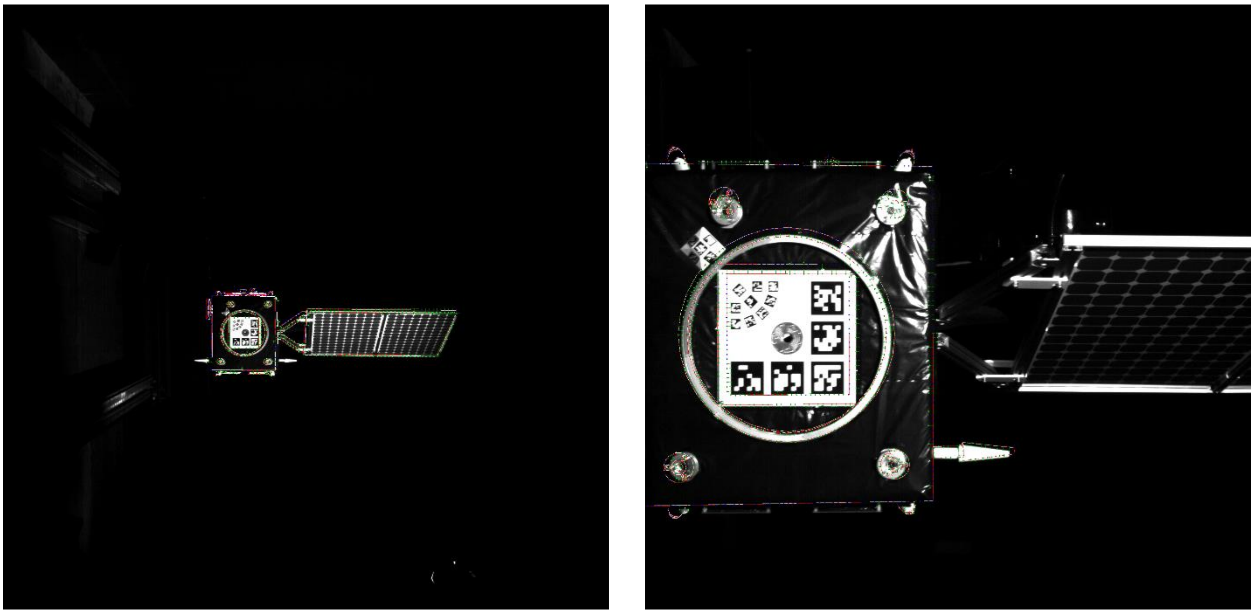


Figure 14 : IP adaptive 3D models re-projected on the Platform-Art© experimental images

4.4 Guidance, Navigation and Control results

From the GNC point of view, the following graphs try to summarize the results obtained in closed-loop with the Image Processing running.

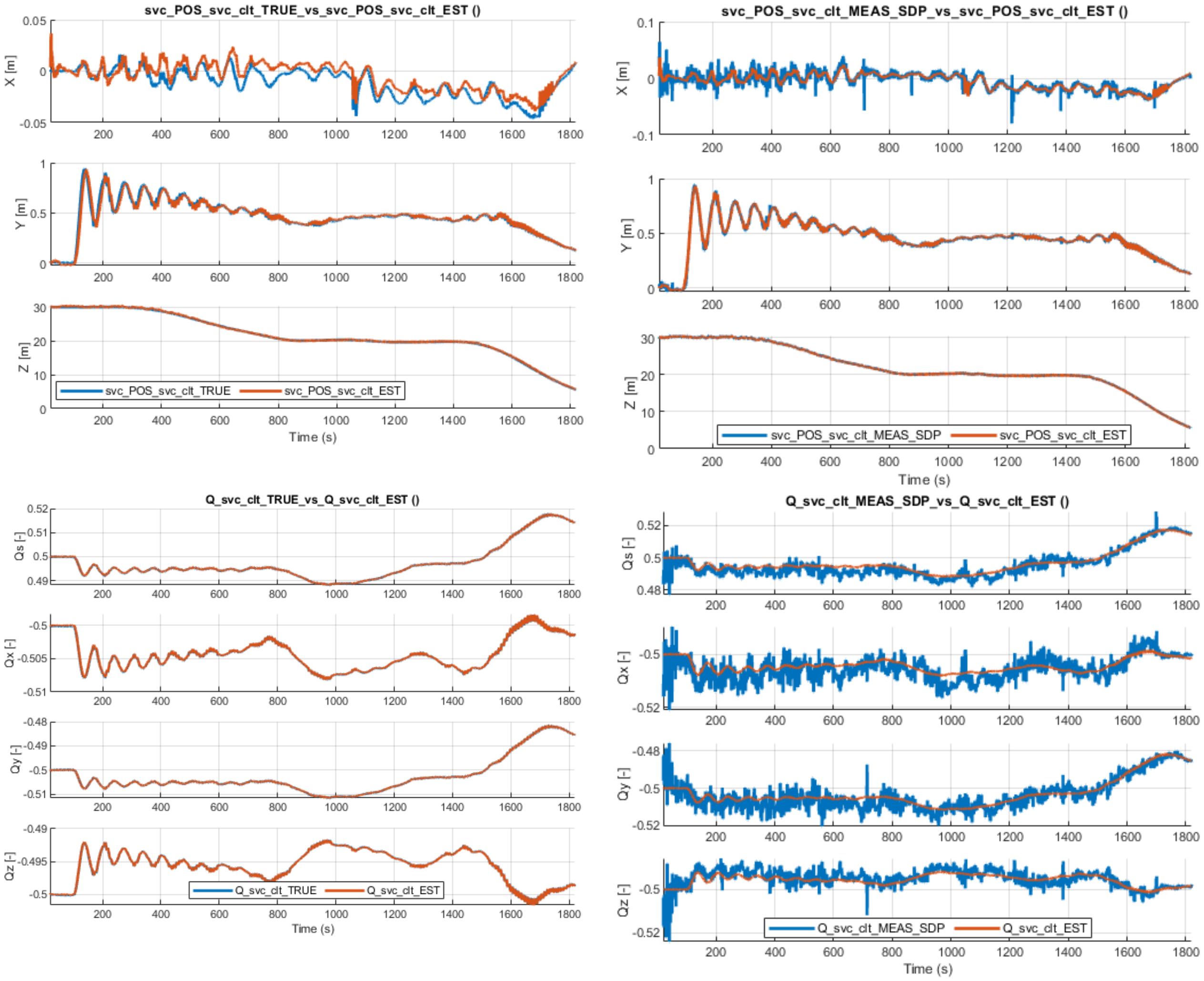


Figure 15 : GNC Performance Analysis in relative Pose on experimental dataset TS0600

The main conclusions drawn from these tests are that the GNC is stable, robust to the illumination conditions and the actuators uncertainties (mainly introduced on the thrusters). The stage of GNC filters and controllers re-tuning proved to be mandatory from the MIL/SIL tests to HIL tests due to the lack of representativity of the draft IP Performance Model in terms of delay and covariance analysis. In addition, the impact of the illumination conditions in terms of Sun elevation angle over the orbital plane: this impact the IP performances by creating shadows and sometimes blinding some parts of the Client, leading to a loss of GNC performances as it can be noticed from the oscillations due to a hard guidance step profile to initially align the cameras with the Client.

The GNC autonomy was also successfully executed with the models logics, and autonomous transitions, which were using an event-based approach on-board in order to reduce the need of complex operations on ground. This level of E3 autonomy according to the ECSS allows to simplify the operations to GO/NO-GO commands as long as the GNC / IP execution is nominal.

5 CONCLUSION

This paper introduces the GNC and IP SW validation followed during the phase A/B1 of the EROSS+ project led by Thales Alenia Space with the support of GMV. The overall mission and system design were introduced to highlight the cameras used and the design of the Client mock-up. The validation process was reviewed from the overall approach from algorithm design and tuning, to autocoding, integration and validation in an embedded real-time system. Eventually the performances of both the IP and the GNC SW have been reviewed along with some concrete example of raw experimental images. The tight coupling between IP and GNC proved to be an advantage as long as the tuning is updated on experimental dataset rather than only on numerical tools. This conclusion also paves the way to update the GNC robust synthesis chain with refined hypotheses regarding the IP modelling.

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