DYNAMIC TEST FACILITIES AS ULTIMATE GROUND VALIDATION STEP FOR SPACE ROBOTICS AND GNC SYSTEMS

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ABSTRACT

Ground testing of space technologies, and in particular space robotics and Guidance Navigation and Control (GNC) ones, is crucial in order to de-risk space missions that heavily rely on them. In this context, this paper describes the role of the ***platform-art©*** robotic facility located at GMV premises in Tres Cantos (Madrid, Spain) as last on-ground validation step within the development and validation of a whole range of different space technologies.

The ***platform-art©*** hardware in-the-loop facility can simulate the dynamics of any satellite system: the paper will present how the facility has been used in a number of activities related to a different space scenarios such as Lunar descent and landing, on-orbit servicing (including contact), active debris removal (e.g. ANDROID mission) and Rendez-Vous (e.g. Mars Sample Return capture mission). The modularity of the facility will also be described, which allows for fast re-adaptation of the setup for different scenarios, also enabled by the different mock-ups that are available at ***platform-art©*** (with different scale factors and fabrication precision depending on the specific test needs. Lessons learnt and graphical results from different ESA projects that have used the ***platform-art©*** hardware in-the-loop facility

It will also be presented, complementary to the dynamic test facility, an integrated Design, Development, Verification and Validation environment covering from Model-in-the-Loop (e.g. Matlab/Simulink algorithms) till real-time Processor-in-the-Loop (with autocoded or hand-made GNC produced SW) and later on extended through the use of dynamic test facilities with real dynamic and air-to-air HW-in-the-Loop (sensors, robotic manipulators, …) stimulation.

Index Terms— Robotic testbench, GNC, Rendez-Vous, Active Debris Removal, On-Orbit Servicing, planetary landing, ground validation

1. INTRODUCTION

Very often, the most state-of-the-art relative GNC related technologies (active debris removal, rendezvous, formation flying, but also planetary/asteroid landing) need to fly as an experiment before being declared validated for space use as mission baseline. In-flight validation opportunities are, nevertheless, expensive and very limited in terms of number of opportunities. This is especially true for new mission concepts in Europe, including Formation Flying, uncooperative Rendez-vous and Docking/capture/grappling applications.

Realistic and extensive ground validation is, today more than ever, mandatory in order to avoid the costly in-flight validation and to reduce the gap between ground and flight testing and validation.

Thus it is mandatory to have space-representative ground testing facilities. GMV experience proved that Dynamic HW-in-The-Loop (HIL) test facilities can effectively provide validation in relevant environment, effectively achieving TRL 5/6 on ground and thus minimizing the uncertainty/risk of such technologies/systems with respect to its operational use. Such facilities shall include realistic space-representative avionics (processor, interfaces and real-time operating system), realistic and air-to-air stimulated breadboard perception sensors (IMU, optical cameras, laser 3D sensors), the use of dynamic robotic devices hosting the active vehicle and debris mock-ups and reproducing accurately the spatial relative dynamic corresponding to an ADR scenario, and full GNC system prototypes.

This paper describes the set-up and results of GMV's ***platform-art©*** dynamic test facility, successfully used for validation purposes of GNC systems and related technologies for a wide variety of space scenarios, including several GNC-related validation test campaigns for different ESA and other European national delegation activities, such as MSR Sample Canister capture, active debris removal ANDROID mission, PRISMA-HARVD flight experiment performed in collaboration with OHB-Sweden through the PRISMA mission, Visual Navigation for Descent and Landing phases in the Moon, asteroid approach and landing, and International Berthing and Docking Mechanism test.

2. DYNAMIC TEST FACILITIES ROLE WITHIN AN INTEGRATED DESIGN, DEVELOPMENT, VERIFICATION AND VALIDATION APPROACH

An already proven efficient approach for the Design, Development, Verification and Validation (DDVV) approach for the GNC needed for any mission, and particularly for relative multi-vehicles missions (such as an Active Debris Removal scenario, a Rendezvous scenario or a Formation Flying scenario), is based on an incremental testing fidelity paradigm based on the well-known integrated chain MIL➔SIL➔PIL➔HIL, where:

- The MIL (Model-In-the-Loop) level is based on the use of a Functional Engineering Simulator (FES) that includes environment SW models and reference models of the selected algorithms (GNC-ALG) and MIL-level prototyped solutions for the on-board GNC system, including GNC, AMM (Autonomous Mission Management function) and FDIR (Failure Detection, Isolation and Recovery) subsystems. The FES is the main conductive design supporting tool and verification tool at algorithm level all along the GNC lifecycle work.
- Hand-made Coding or Autocoding techniques can be used to translate MIL-level prototyped solutions for the on-board GNC system (GNC, AMM, FDIR) into C code and start the SW V&V process. A SW in the Loop (SIL) verification step by integrating the produced GNC-SW in the FES simulator shall be afforded before going to the PIL test benches in order to verify the correctness of the algorithms SW coding. In this stage, the SIL V&V level is achieved.
- The PIL (Processor-In-the-Loop) test bench/es shall cover the integration of the GNC-SW in a real-time and space-representative avionics platform. The PIL test bench/es will allow testing the GNC-SW in flight realistic conditions regarding the avionics (real-time, and representative chaser spacecraft processor/s flight models) and with simulated environmental conditions. In this stage, the PIL V&V level is achieved.
- The dynamic (HW-In-the Loop) HIL/Sensors test bench is the logical and ultimate extension of the PIL test bench/es (where the former PIL test bench will be used as an integral part of the dynamic HIL/Sensors test bench, thus already including the GNC-SW). This test bench is the last step within the on-ground GNC validation and verification chain and provides real dynamic conditions reproduction that stimulates real HW sensors with air-to-air signals so as to achieve the maximum ground testing level (HIL level, TRL 5-6) regarding the achieved representativity of the flight conditions.

Following Figure 1: Coherent, incremental, highly automated GNC Design, Development, Verification and Validation (DDVV) Approach presents a diagram with the integrated and incremental GNC Design, Development, Verification and Validation (DDVV) approach.

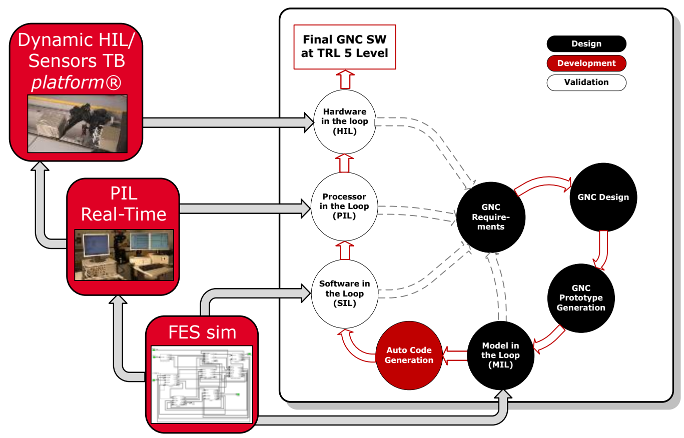

Figure 1: Coherent, incremental, highly automated GNC Design, Development, Verification and Validation (DDVV) Approach

3. *PLATFORM-ART©* DYNAMIC TEST BENCH

platform-art© is the GMV's developed and owned test bench to allow supporting the verification and validation of the Guidance, Navigation and Control (GNC) systems for short range phases of rendezvous, formation flying and ADR missions, as far as other relative scenarios such as planetary or asteroid landing. [1] [4] [7].

The hardware architecture (see Figure 2: platform-art© dynamic test bench architecture) of the dynamic test bench is composed by:

- ***platform-art©* Avionics** (Real-time PIL test bench components, bottom part of Figure 2): Real time Processor In the Loop (PIL) test bench, where the stimulation to optical/laser sensors is directly provided by the moving platform facility elements and the use of realistically manufactured mock-ups.
- **platform-art© Mechatronics** (Motion Facility, upper part of Figure 2**):** Robotic motion facility, which has been built taken into account some important considerations and components: First, the presence of heterogeneous HW together with the need for executing a chain of hierarchical tasks (specific for each device in some cases) makes suitable the selection of a distributed computing

architecture based on the use of the "distributed objects architecture" paradigm. The major specific elements using the distributed computing architecture are:

- **The Motion Control System**. It is the application in charge of interfacing the robotic and illumination system and controlling the execution inside test bench. It will receive the kinematics information from the Real World simulator through UDP messages and will process it by performing the following tasks: Motion frames conversion; Motion solving for the different mechanical devices; Safety checks; and send the motion solution to each of the specific control applications (of the robotic arms, track and illumination system) and trigger its execution in a synchronised way.
- **The 2xKUKA KR C2 controller systems**. Each controller will receive its motion solution from the Motion Control System and execute the motion command for the each KUKA robotic arm (one of them combined with the long-rail track) motion system. The controller systems are also in charge of collecting the status and diagnostic information from the KUKA devices on demand from the Motion Control System. They are connected through Ethernet and a Wireless adapter to the Motion Control Systems.

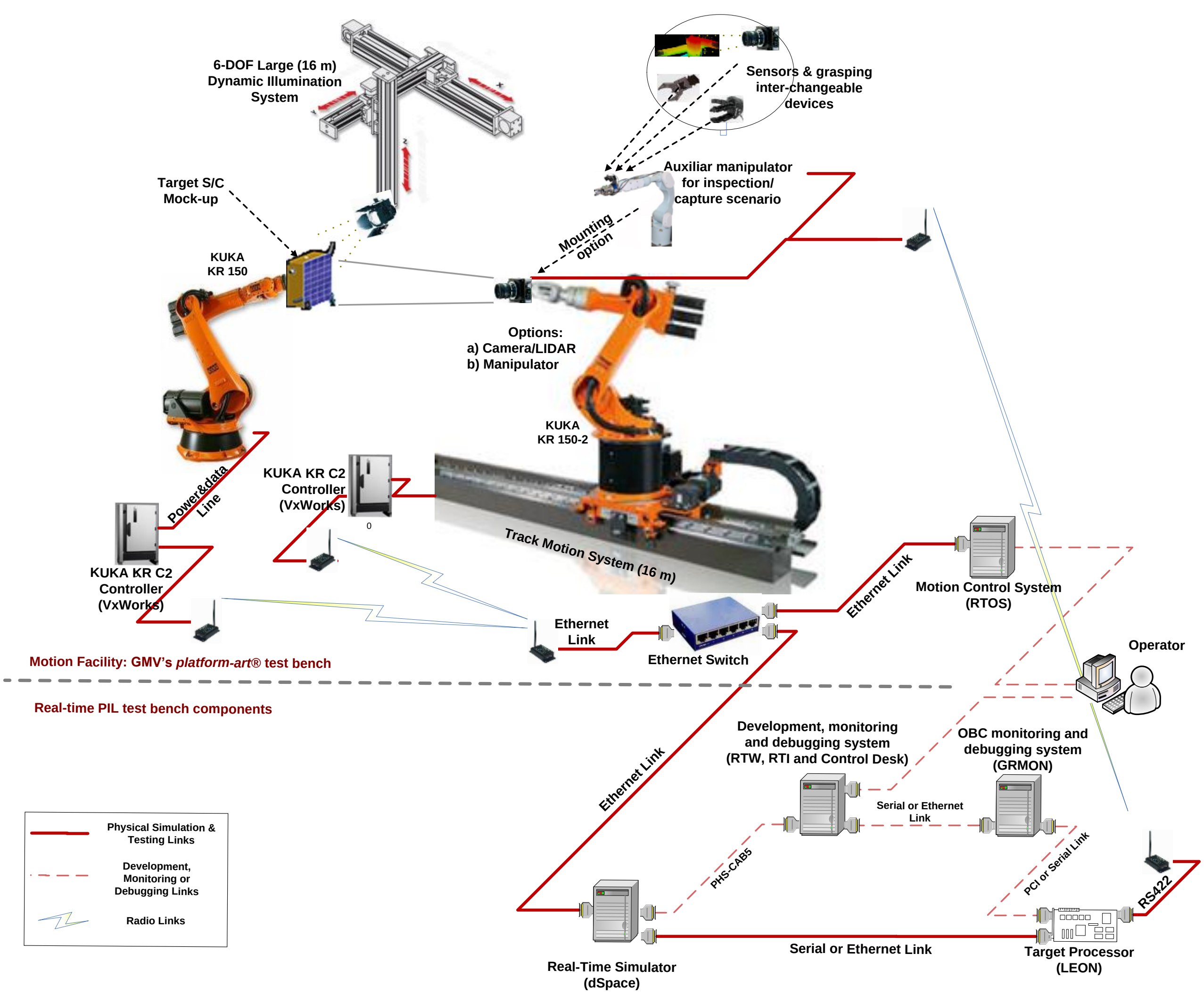

Figure 2: ***platform-art©*** **dynamic test bench architecture**

- **The illumination control system**. The illumination system includes a sun-representative lamp hosted on a long-range (16 meters) 6-Degrees of Freedom Cartesian system. The illumination system receives its motion solution from the Motion Control System and translate them into motion commands for the 6-DOF Cartesian system actuators. It also collects status and diagnostic information on demand from the Motion Control System. Ethernet connection is used as interfacing element to the Motion Control System.
- **The Mitsubishi PA-10 control system**. This light and versatile robotic manipulator can be used either as auxiliary laboratory tool (it has been used, for instance, as part of the illumination system to host the illumination lamp for reduced-range tests) or either as on-board spacecraft manipulator for capture/debris purposes/scenarios. The PA-10 receives its respective motion solution from the Motion Control System and translate them into motion commands for the Mitsubishi PA-10 robotic arm. It also collects status and diagnostic information on demand from the Motion Control System. Ethernet connection is used as interfacing element to the Motion Control System.

Other considerations and elements include:

- The SW applications are implemented over Real Time OS (LinuxRT or RTAI when not imposed by the HW available; e.g. VxWorks in the KUKA KR C2) in order to allow controlling tasks priorities and deadlines. It allows assuring that the motion system executes the commands and consequently the vehicles state is physically reproduced in a time compatible with the real-time PIL closed loop.
- The net architecture selected is Ethernet at link level, IP at net level and UDP or TCP at transport level. Ethernet is a cheap and flexible solution but certainly it can not be considered as a Real Time net due to the fact that relies on the CSMA/CD net access control protocol. Nevertheless, in practice and for low dynamics scenarios (e.g. rendezvous, formation flying, ADR) the effect is negligible.
- Camera System (Lidar or other type of sensors are also possible) composed by the camera acquisition system and the Image Processing
- Different mock-up models as per required scenarios

The main functional features of the ***platform-art©*** test bench can be summarized in the following:

Functional features:

- Dynamic test bench with real air-to-air metrology stimulation
- Raises the GNC S/S (SW+sensors) validation till level 5/6 (ESA scale)
- Two numerically controlled robotic arms + 15 m length rail, allowing Short-range RdV, FF and/or ADR scenarios (up to 525 meters using scalability factor 1:35, reasonable for 1 m S/C size level; can be higher for bigger S/C), including GNC mode transition, scenario stop/resume, change of sensors, …

Performance features:

- Dynamic range: 18 m
- Calibration Accuracy: 0.1 mm (through FARO laser tracker)
- Resolution: < 0.01 mm
- Repeatability: < 0.1 mm
- Mock-ups (Inc. metrology): up to 1 m size, 150 kg, sensors remote control
- Darkness: full darkness room (optical spectrum)
- Illumination: space representative at optical spectrum
- Location/Access: GMV head-quarters (Madrid)
- Others: WIFI, canteen, offices, meeting rooms, …

4. *PLATFORM-ART©* VALIDATION USE CASES

The following sections provide some examples of the use cases of platform-art© laboratory as validation platform.

4.1. IBDM Breadboard Docking Tests

GMV's ***platform-art©*** laboratory (version 2010) was adapted and prepared to host and support the closed loop contact/capture tests and the test campaigns performed by SENER of the IBDM Avionics and Soft Docking System (SDS) Engineering Development Units (EDU) within Phase 2 of the CSTS BreadBoarding activities.

The tests considered contact between active and passive parts of the item under test. Simplified docking or berthing approach was performed, with the objective of raising the TRL of the hardware involved – the IBDM EDU– from TRL 3 up to TRL 4.

Main outcome from this experience was that the stiffness of the mechanical elements (both within the IBDM EDU and with the laboratory robotics arms to recreate the space dynamic) shall be very carefully analyzed/tuned/adapted if the intention is to reproduce space-representative contact conditions. This has been further analysed and understood in the later ROSPA activity (presented in ICATT within a dedicated paper).

Figure 3: Support of *platform-art©* to IBDM EDU contact/docking tests

4.2. HARVD (2010)

GMV has led the ESA's TRP Study: HARVD: Integrated Multi-Range RDV Control System – Autonomous RDV GNC Test Facility. The HARVD activity lead to the development of a highly autonomous on-board S/W demonstrator in charge of providing docking or capture capabilities starting from long range initial conditions around Mars and Earth, in circular and elliptical orbits. HARVD includes SW prototyping of a GNC/AMM/FDIR system, including preliminary design, detailed design, modelling and SW coding. [8].

HARVD DDVV approach followed the (at that time innovative) integrated and incremental MIL➔SIL➔PIL➔HIL DDVV approach, with the last HIL step relying in a Real-Time Dynamic test bench (***platform-art©*** former set-up), based on 2x6 DOF robotic arm, one of them.

The use of the dynamic HIL test bench allowed to detect a critical feature about the long processing/delivering time required by the main navigation sensor (a 3D LIDAR) to provide the Sample Canister position/range estimation within the LIDAR Field of View. This effect required a quite significant re-tune of the GNC algorithms (mainly on the Kalman filter and on the Guidance corrective manoeuvres) in order to fulfil with the capture/docking requirements.

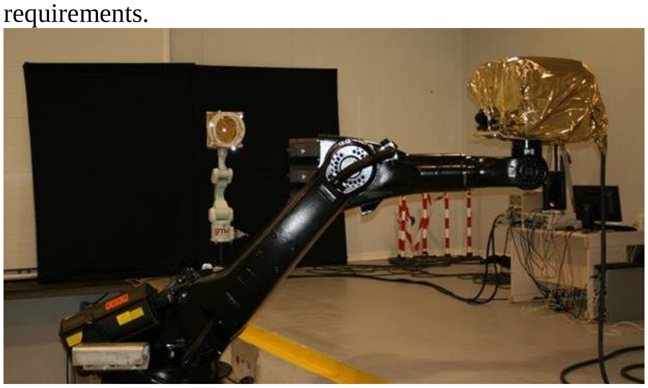

Figure 4: Servicing docking scenario dynamic test set-up during HARVD activity

4.3. PRISMA-HARVD (2012) – Cross-Validation of *platform-art©* with flight data

The main objectives of this activity (ESA Aurora program) were to define, develop and execute an off-line experiment for which PRISMA in-flight data would be used for:

- Testing and validating up to TRL 6 the HARVD GNC SW demonstrator;
- Calibrating and validating the rendezvous dynamic test bench (***platform-art©***).

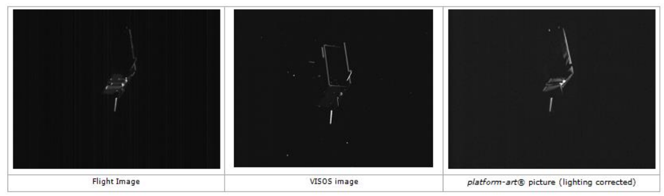

Figure 5: PRISMA flight picture (left), simulator image (central), platform-art image (right)

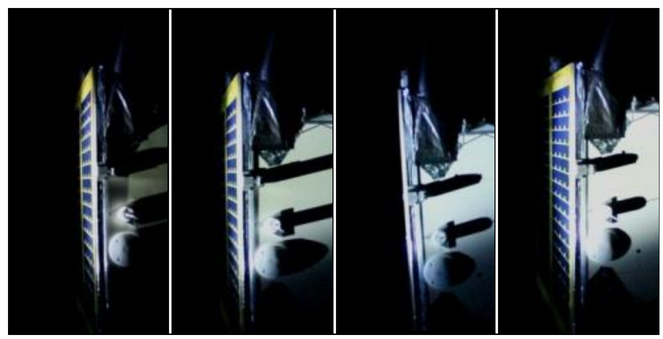

Figure 6: Sequence of short-range PRISMA-TANGO S/C mockup lab images with different illumination directions

4.4. iGNC (2015) – Mars Sample Return Tests

The Integrated GNC (iGNC) is an activity aimed at designing, developing, verifying and validating in a very high fidelity environment the GNC for autonomous rendezvous and capture phase of the Mars Sample Return (MSR) mission as defined during the Mars Sample Return Orbiter (MSRO) ESA study. The validation cycle includes testing in an end-to-end simulator, in a real-time avionics-representative test bench and, finally, in two HW-in-the-loop test benches (one optical and **one dynamic**) for assessing the feasibility, performances and figure of merits of the baseline approach defined during the MSRO study, for both nominal and contingency scenarios. [5].

The On-board software (OBSW) is tailored to work with the sensors, actuators and orbits baseline proposed in MSRO. The whole rendezvous is based on optical navigation, aided by RF-doppler during the search and first orbit determination of the Orbiting Sample (OS). Real camera images are injected in the loop, processed by Image Processing (IP) obtain the observables to feed navigation function. The rendezvous phase includes the non-linear orbit synchronization, based on a dedicated non-linear guidance algorithm robust to Mars Ascent Vehicle (MAV) injection accuracy or MAV failures resulting in elliptic target orbits.

The robustness of the developed GNC/AMM/FDIR has been verified by mean of a very extensive test campaign, including (integrated DDVV approach) MIL, SIL, PIL and, finally, HIL tests within the dynamic test bench. The use of the dynamic test bench has allowed:

- In some cases, to verify the hypothesis made at MIL level for the design of the GNC algorithms.
- In other cases, to correctly tune the MIL simulator with real HW experimental observations obtained from the dynamic test bench results (data communication delays, HW-related processing times, HW-related error parameters, flight libraries mismatching with MIL libraries, scheduling, …). In those cases, an iteration of the GNC system design at MIL level has been required. The integrated MIL➔SIL➔PIL➔HIL DDVV approach has allowed to go forward and backward in this chain very quickly, with a 2-weeks typical iteration period.

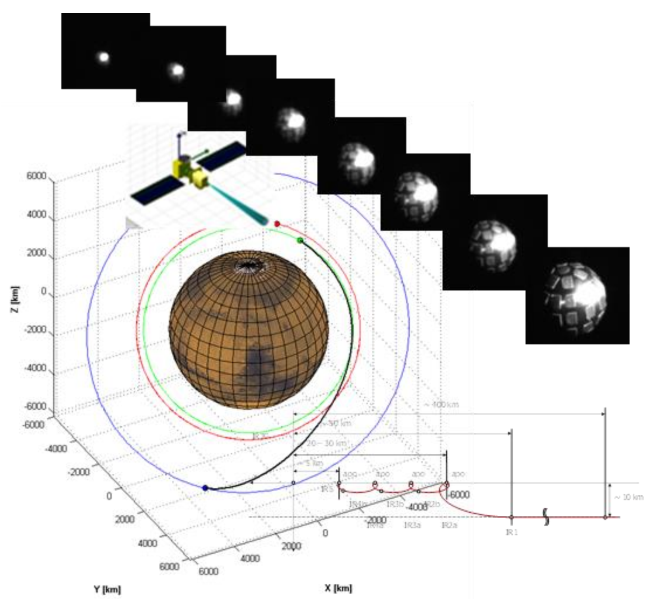

Figure 7: MSR Sample Capture phase and real images obtained during dynamic HIL testing campaign

4.5. ANDROID (2014)

GMV/QS ANDROID activity has performed a conceptual design of an Active Debris Removal (ADR) Demonstration Mission on a small (<130 kg) uncooperative target (PROBA2) using a small mission/satellite, with the main goals of:

- Demonstrate GNC technologies for RdV and Capture for ADR purposes
- Demonstrate two capture techniques:
  - Rigid combo: Robotic Arm
  - Non-rigid combo: Net
- Deorbit PROBA 2 satellite

This activity ended with a reproduction in ***platform-art©***) of the approach phase of the ANDROID satellite to a PROBA2 mockup for generation of an space-representative image database for later use as representative 2D images for visual-based navigation purposes. These images have been later used for internal GMV activities related to pose estimation (position, velocity) through Image Processing techniques validation.

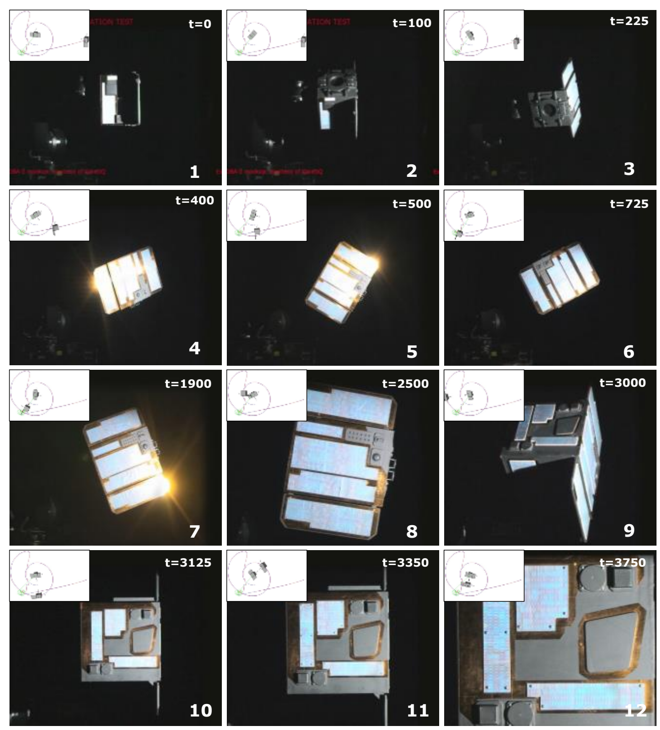

Figure 8: Sequence of laboratory images during ANDROID approach to PROBA2 satellite

4.6. VISONE (2012)

During ESA-LL-B1 activities, the necessity of Vision Based Absolute Navigation technology was remarked as fundamental in order to achieve pin-point automated lunar landing.

Building on top of well-known GMV's ANTARES system, GMV-Romania was awarded by the Romanian Space Agency (ROSA) a contract under the national STAR programme devoted to make the ANTARES system generic and reliable for any lunar mission scenario (either orbital or landing scenarios). [6].

After several validation steps, including Model-In-the-Loop (algorithm level) and optical laboratory (synthetic images projected in front of a camera device) validation steps, the final technology maturation step has been to test it in a dynamic Hardware-in-the-Loop laboratory set-up, composed by a South Pole Lunar surface mock-up, a camera mounted as end-effector on one of the GMV's ***platform-art©***) robotic arms and the illumination system.

Figure 9 shows the milled surface mockup during calibration tests. Figure 10 shows an example of image obtained in the test environment and processed by the algorithm. The most challenging aspect during the tests were the very high used scale factor (1:500000) that made the calibration to be a very critical point.

Figure 9: Preparing the dynamic HIL tests set-up

Figure 10: Example of Image obtained in the test environment

4.7. NEO-GNC (2014-2015)

An autonomous GNC system for descent and landing (D&L) has been developed by a consortium led by GMV under ESA contract. The objectives of the autonomous GNC system are to enable flexible, robust proximity operations for different strategies and to minimize the development and operation costs. The GNC system is based on advanced algorithms fitting into existing flight processors, and low-cost, European navigation sensors (wide-angle camera, laser altimeter, star-tracker, IMU). [2] [3].

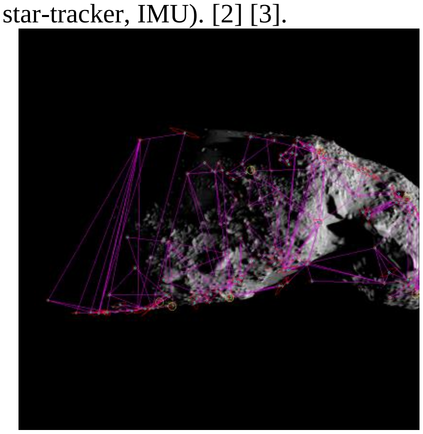

Figure 11: First image of a D&L phase from inertial hovering close to Equator (lines show the landmark database used for initialization, yellow circles show unknown landmarks)

Final step of the designed GNC algorithms have been to test them in real-time in an avionics/dynamic testing environment. The dynamic test environment has been provided by a dedicated set-up of GMV's ***platform-art©*** laboratory. Use of NPAL camera breadboard (Airbus) and laboratory COTS cameras have provided worth data for maturing the technology. Finally, the technology and asteroid has been also tested within the ESA/NASA AIM/AIDA mission scenario (including the use of a mockup with scale factor 1:800 of the secondary asteroid, called "Didymoon").

Figure 12: Laboratory set-up image

5. CONCLUSIONS

This paper started by stating the role of dynamic testing facilities as ultimate ground validation step.

GMV's ***platform-art©*** laboratory has been used in the last 10 years as validation test bench for more than 20 (GMV internal as well as external for ESA and other European space agencies) space-related technologies/applications. In all of them (ranging from Lunar descent and landing, asteroid sample return, on-orbit servicing, active debris removal and Rendez-Vous and capture in Mars), the dynamic laboratory has demonstrated to be a valuable and cost-effective resource for maturing and raising the technologies/systems/sensors TRL level.

The key factor to service such variety of missions/scenarios is modularity and flexibility, together with a deep knowledge of the different involved scenarios by the laboratory engineers, allowing them to quickly identify the key aspects of each application/technology scenario and set-up the laboratory in consequence (e.g. scale factor/calibration, illumination, real-time, communication delays, distributed processing, …).

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