ROBOTIC ARCHITECTURE AND OPERATIONAL CONCEPT FOR IN-SPACE ASSEMBLY AND SERVICING MISSIONS

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ABSTRACT

The future of spaceflight will relay more and more on robotic systems. These systems will enable the next generation of spacecraft's infrastructure and services in orbit. The European Union has implemented an ambitious program to demonstrate in orbit how those technologies will be of use to realize robotic systems needed to support in-space manufacturing, assembly and servicing. The PERIOD project is developing the needed building blocks further and preparing an in orbit demonstration hosted on the Bartolomeo platform outside of the Columbus module. This paper provides a description of the PERIOD mission, its robotic architecture and the operations concept to demonstrate the assembly of a reflector in orbit and the reconfiguration of a small satellite.

1. MOTIVATION

Companies and agencies in the space business are preparing robotic systems and mission, as there is a strong indication that the next decade will be driven by the commercialization of LEO and GEO [1]. This is reflected by roadmaps and development in various fields and by several agencies. In parallel the trend to larger launchers with bigger fairings to transport larger systems or equipment needed in orbit can already be observed. Telescopes are getting bigger as well as reflectors for telecommunication antennas and the plans for large space data centres, space based solar power and the next space stations are already existing. The capacity to launch such systems fully integrated even on a heavy launcher is limited and due to that, In-Space Manufacturing and Assembly (ISMA) is considered as a major enabler for the space business in the next decades [2]. The ISMA processes can be realized with astronauts as it was done for the ISS and the repair of the Hubble telescope, but the harsh environment and the cost for human spaceflight increase the need for robotic ISMA and servicing missions [3].

The PERIOD (PERASPERA In-Orbit Demonstration) currently under preparation has the goal to demonstrate in orbit on the ISS key robotic technologies to enable ISMA and OOS (On-Orbit Servicing) applications. The set-up can be seen in Figure 1 with two payload boxes, one equipped with the robotic system and one equipped with the satellite and reflector parts.

The PERIOD project is one of the operational grants (OGs) of the third phase of the Horizon 2020 Space Strategic Research Cluster (SRC) on Space Robotics Technologies. Outcomes of previous OGs from the first and second call will be implemented and further developed. PERIOD seeks to change the status quo by demonstrating an alternative to the traditional approach of manufacturing, assembling, and validating space hardware on the ground with direct in-orbit manufacturing and assembly using robotics, autonomy, and modularity.

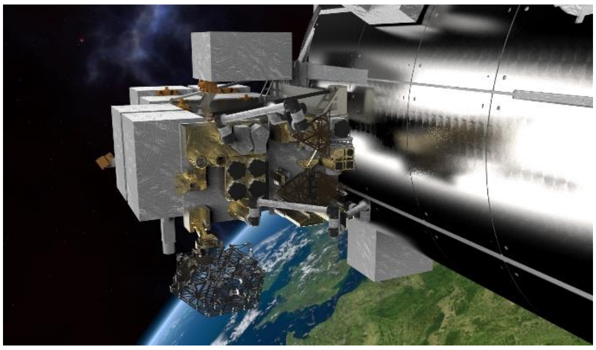

Figure 1 – The PERIOD Boxes mounted on the Bartolomeo platform outside of the Columbus module

The advantages are that there are no longer constraints on the overall volume and design of large satellite antennas, telescopes and structures. Multiple opportunities exist as there is a need to build larger space infrastructures such as modular space stations and lunar surface infrastructures. In addition, ISMA technologies would enable affordable upgrade and repair of existing spacecrafts and satellites, promoting the sustainable use of space through plug-and-play modularity.

The ISMA industry can revolutionize the space market by creating a sustainable space ecosystem and providing new services [5]. Payloads will be autonomously exchanged on reconfigurable standard satellites. Most satellites will be repaired, serviced, or removed from orbit in space, which means we can better mitigate the space debris problem.

The specific objectives of the PERIOD project in Phase A/B1 are to further develop the core software technologies ESROCOS, ERGO and InFuse (OGs of the first PERASPERA call) to reach TRL5, evaluate the available standard interconnect (SI) components (SIROM, HOTDOCK, iSSI) for the assembly demonstration in a benchmark, and also evaluate the assembly capability in a breadboard with the use of ESROCOS, ERGO, InFuse, I3DS and the SIs,

Furthermore, the objective is to define a concept for an orbital demonstrator along with the system requirements for satellite manufacturing and assembly, as well as for attachment and refuelling. Successful implementation of these objectives will lead to the creation of independent European capabilities that will enable Europe to build future orbital infrastructure and compete in ISMA markets.

2. MISSION DESCRIPTION AND OPERATIONS

The PERIOD mission serves the objective to demonstrate in orbit the robotic capabilities needed to support assembly, manufacturing and refuelling servicing tasks. The mission statement is defined as follows:

"Demonstrating ISMA capabilities, the PERIOD mission will initiate the transformation of the lifecycle of space systems toward higher value, higher resilience, higher system capacities and lower capital expense, and toward independent European capabilities allowing Europe building the future orbital infrastructure and being competitive on the ISMA market."

The mission is planed with a total duration of six years. The KO was in January 2021 and the on ground delivery (OGD) is planned for 2025. The In-Orbit demonstration will be conducted in 2025 & 2026 including decommission of the boxes and the demonstration satellite. All phases from the development to the disposal of the factory are depicted in Figure 2.

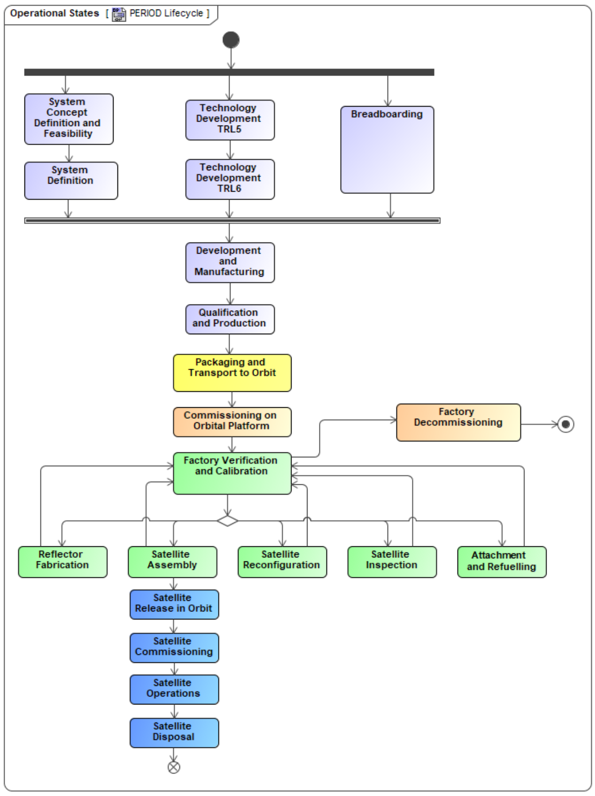

Figure 2 – The PERIOD Lifecycle in the MBSE model

Once the factory is commissioned on the orbital platform, the technical part of the demonstration begins with the assembly of the antenna reflector and subsequent verification, assembly of the satellite, reconfiguration of the satellite, inspection of the satellite. Upon completion of the satellite assembly and inspection, the satellite will be released from the ISS in LEO for an independent mission demonstrating the full operational capabilities of the satellite, including ground communications using the built antenna reflector.

Constraints:

The main constraints coming from the ISS are associated with the human space flight environment, the sizes of the airlocks and BTL boxes and the importance of not disturbing or blocking other experiments on the ISS, Columbus or the Bartolomeo platform. The robotic movements of the PERIOD system will introduce vibrations and shocks into the BTL platform. Therefore, very slow movements are either necessary or a coordination with the other experiments on BLT.

- ISS constraints
  - Size of the airlocks
  - Safety of the ISS crew
  - Kick loads of astronauts should be considered
- Bartolomeo constraints
  - Box volume limitation
  - Box mass limitation
  - Low disturbance
  - Stiffness BTL boxes
  - No negative effect on experiments on Columbus and Bartolomeo allowed
- MSS constraints
  - Reachability of boxes for handling (Access corridor)
  - Limited power supply during transfer with interruptions
  - Shock from MSS during extra-vehicular robotics (EVR)
  - Shocks allowed to be introduced to the MSS
- Environmental Conditions
  - Micro-meteoroid and orbital debris
  - Atomic oxygen
  - Pressure Environment
  - Plasma environment
  - Radiation Environment
  - Thermal Environment

Despite these limitations, the Bartolomeo platform offers many ways to keep the system simple and thus develop it cheaply and quickly.

3. SYSTEM CONCEPT & ARCHITECTURE

The purpose of the IOD mission is to develop, test, and validate robotic technologies and operations in orbit. In order to focus resources on this essential objective, the development effort and costs for the orbital carrier platform, the transport logistics as well as the supply and communication infrastructure should be kept as low as possible. Therefore, the system concept foresees the Bartolomeo platform on the Columbus module of the ISS as the carrier platform. The platform, the transport logistics as well as infrastructure are already existing and available at comparable low costs, risks and potential impacts on the schedule. Bartolomeo provides twelve payload slots of which two shall be utilized by the PERIOD system.

Hence, all the hardware needed to perform the mission is accommodated to fit inside the volume given by the Bartolomeo specification. Indeed, Bartolomeo request to accommodate the mission inside boxes that are connected to the station through the Gold2 interface. The PERIOD mission is then split into two different boxes. The first box, so called “Factory Box” contain all the element to form a standalone in space factory.

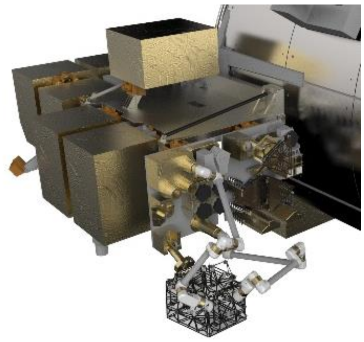

Figure 3 – Bartolomeo Platform at Columbus Module of ISS

The second box, so called “Satellite Kit Box” contain all the elementary parts that will be assembled to form the mission, so it can be exchanged depending on the mission.

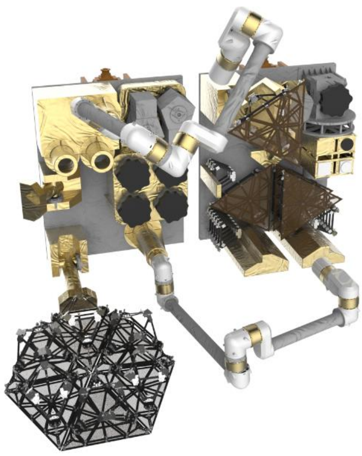

Figure 4 – PERIOD Boxes during Operation

Nevertheless, the overall concept is designed to be as modular as possible, with the ability to be flexibly arranged in other configurations for accommodation on other carrier platforms in future follow-on missions.

As explained before, the Factory Box contains the Providing Service elements of the orbital factory:

- **Manipulation System** consisting of two 6-DoF manipulators, each equipped with a Standard Interconnect and a camera system at its end-effector, to perform the visual-based control during the assembly process thereby increasing the positioning accuracy. The cameras are also used to perform measurement (photogrammetry) of the reflector. The manipulators are composed of exchangeable actuator modules and able to maintain each other in order to provide redundancy.
- **Set of tools** that can be connected to the end-effector of a manipulator. The tools are designed using a product approach with a Multi-Purpose Tool integrating the controller and actuator of the tool socket.
- **Tool magazine** as storage which can be used for temporary storage of tools not required.
- **Workbench elements** are used during the reflector assembly process to hold and position the parts. The workbenches also have deployment and orientation capabilities to enable positioning of the interface with regard to the manipulators. The end-effector of the workbench is equipped with a swappable interface in order to perform workbench reconfiguration.
- **Robot Control Unit (RCU) and Power Conditioning Unit (PCU)** for data processing and power conversion.
- **Firmware and operating system:**
  - Robot operating control system (ESROCOS) implements the open-source framework for supporting the development of all robot control software applications in PERIOD ISMA Factory.
  - Autonomy framework (ERGO) implements the planning and acting capabilities of the factory.
  - Sensor data fusion framework (Infuse) implements the perception capabilities of the factory.

The Satellite Kit Box contains all the Receiving Service elements of the orbital factory:

- **Storage (dispenser)** for all parts of the satellite antenna reflector such as the reflective surfaces and structural frames as well as for the boom to connect the antenna reflector to the satellite.
- **CubeSat core module** (with its Kaber deployer in case of deployment) and associated CubeSat payload module. The two modules are equipped with standard interfaces to be able to connect them together and allow connection with the manipulators.

The software architecture integrates the required components of the different software building blocks (ESROCOS, ERGO, InFuse and I3DS), which have initially been developed in previous EU H2020 SRC PERASPERA[1] activities, and foresees a distributed deployment with interfacing between ground and the space segment to realize a shared autonomy concept. As shown in Figure 5, the ground segment will include the Robot Control Station as well as the On-Ground Robot Operation Control Software which will include instances of all software components of the robot control system. This will allow to perform a complete operational sequence validation by interfacing and utilizing the simulation on-ground as a virtual testbed before execution using the real hardware on the space segment.

Due to calculation and memory effort as well as dependencies on external libraries, planning components of ERGO (e.g. mission planner Stellar and robotic arm motion planner RAMP) and pose-estimation of InFuse are foreseen to be instantiated within a TASTE/ESROCOS deployment only on-ground. Whereas instances of the components required for (semi-) autonomous supervised execution of the plans through real-time control of the robotic system will run in the space segment as part of the On-Board Robot Operation Control Software. This way an on-board autonomy ECSS level of E3 will be achieved. The option to shift the ERGO and InFuse components running on-ground in the first instance, to the TASTE/ESROCOS deployment of the space segment later in Phase D will be investigated in order to test it and thereby achieve autonomy ECSS level E4.

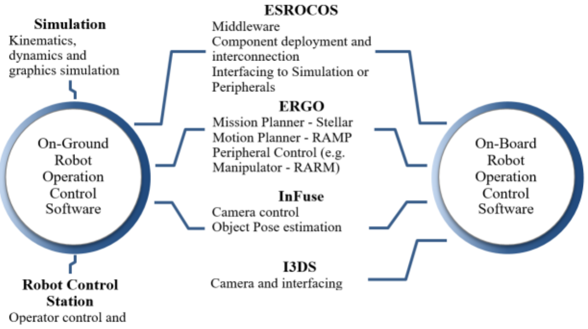

Figure 5 – Distribution of Software Components between Ground- and Space-Segment

As Robot Control Unit on the space segment, a radiation tolerant Atom based PC-104 board with a stack of

[1] https://www.h2020-peraspera.eu/

existing interface cards, which is already utilized on Bartolomeo, with a Linux operating system is foreseen as a basis for ESROCOS to provide sufficient performance and interfacing capabilities to the systems peripherals. Nevertheless; future applications, e.g. in GEO, might require a radiation hard RCU solution. Therefore, portability of the control software to potential applicable components, such as DAHLIA[2], is already taken in consideration as well.

4. SUBSYSTEMS

The robotic subsystems are a major part of this IOD. Most of them have been developed in the last years and their final validation will be alongside the system validation in orbit. The main subsystems will be described shortly hereafter.

4.1 ROBOTIC MANIPULATOR

Airbus' robotic manipulator known as the Versatile In-Space and Planetary Arm, or VISPA (see Figure 6), is a cost efficient, modular multipurpose robotic arm targeted at next generation space activities such as servicing, assembly, manufacturing, and active debris removal.

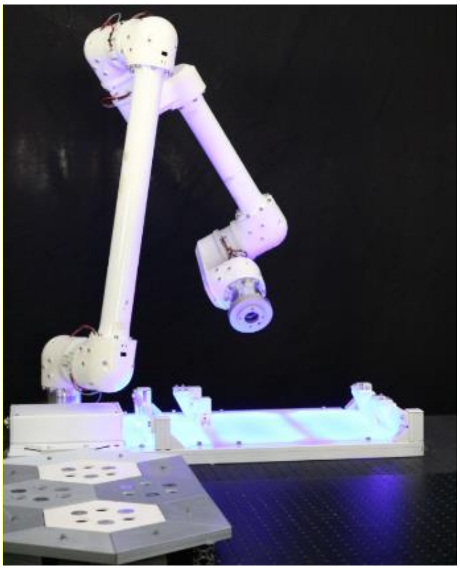

Figure 6 – The VISPA Manipulator

Consisting of six identical joints providing 6 degrees of freedom (DOF), a maximum reach of 1.8 metres, current mass of ~14.5kg, communication via CANbus and SpaceWire, and a zero-g payload capable of manoeuvring medium sized satellites. A key feature of this development is the target end cost of the product to make it an affordable product while minimising the technical compromises.

4.2 TOOLS

The robotic tools follow a modular approach, starting with the avionics board, which can be reconfigured so that it can also be used to control and monitor the tool magazine and workbenches, and ending with the interchangeable tool mounts/extensions driven by the core module. This module is called the Multi Purpose Tool (MPT) and includes the avionics boards, the end effector camera, and an interface with a drive shaft to actuate the tool mounts, as well as an interface to the last joint of the VISPA manipulator [4]. The breadboard of this system is depicted in Figure 7 with the cube-sat gripper and a cube-sat mock-up.

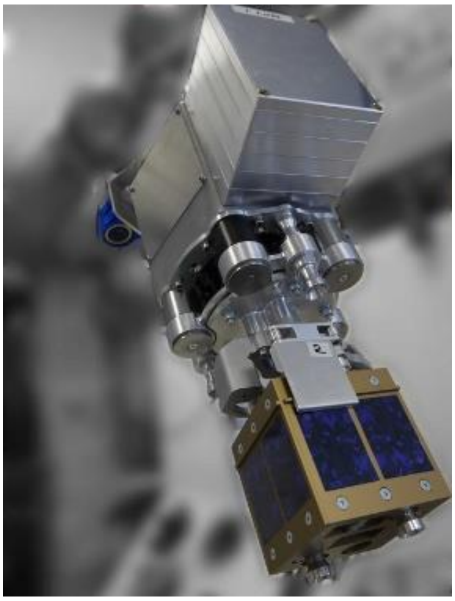

Figure 7 – The Multi-Purpose Tool with Cube Sat Gripper and a cube sat module

For the PERIOD mission, the factory box will have three MPTs and four sockets. A socket to screw the antenna parts together and adjust the antenna shape, a frame gripper to hold the larger antenna frames and the assembled reflector, a lug gripper to grab the small lugs used to connect the structural frames, and a joint change gripper to change the actuators of the VISPA arm.

4.3 STANDARD INTERCONNECTS

The mentioned standard interconnects are multifunctional intersections that allow e.g. modules or systems equipped with an SI to be interconnected. In the example of the Factory in PERIOD, the idea is that

[2] https://dahlia-h2020.eu/

different modules with different functions and features are connected to each other so that, for example, a satellite is created. An SI can couple the modules mechanically as well as transmit electrical power and data. For the demonstration scenario in PERIOD, three different standard interconnects (HOTDOCK, SIROM and iSSI) were tested in the so-called SI benchmark ring. The goal is to give a recommendation for one of these three standard interconnects [6][7].

4.3.1 HOTDOCK

HotDock is a sensorized multifunctional androgynous interconnect developed to address the needs of future OSAM applications (see Figure 8). Its form fit geometry is optimized for robotic operations, allowing for a large misalignment and vision-less mating.

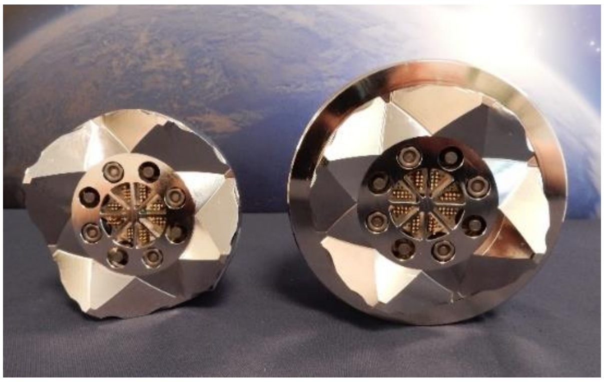

Figure 8 – HOTDOCK interface (passive and active, with fluid transfer connectors)

Its patented locking mechanism allows for high loads (3000N tested) and torques transfer (600 Nm tested – active/active configuration). In addition, HOTDOCK allows for high power and data transfer, as well as fluid transfer. HOTDOCK was successfully used in space robotics breadboard demonstrators of EC projects MOSAR, PULSAR and PRO-ACT, and is being used in ongoing EC projects PERIOD and EROSS+. HOTDOCK is also used in ESA (MIRROR) and NASA (MTU / T-REX) studies.

4.3.2 SIROM

SIROM is designed as an androgynous interface allowing easy mating/demating with other SIROMs (see Figure 9). Its high capture latches are based on the docking system of ISS Columbus module. This, combined with its guiding petals, provide SIROM a self-aligning capability tolerant to very large misalignment conditions. The docking system keeps the locked position without the need of friction brakes or power consumption. Also, SIROM features a capture switch independent of illumination conditions, that gives information once two SIROMs are within the latching capture range. Once mechanically latched, SIROM deploys its connectors board to establish a physical plug for data, electrical power transmission and fluid transmission (optionally).

Figure 9 – Active SIROM (left), Passive SIROM (right). PERIOD benchmarking versions

4.4 REFUELLING INTERFACE ASSIST

ASSIST is an ESA initiative towards standardization for on-orbit servicing of satellites refuelling; covering the grasping, fuel transfer and data exchange to support the refuelling operations (see Figure 10). A first version of ASSIST provided a full-scale mechanical model manufactured to test the mating and fuel transfer operations. This breadboard model allowed reaching TRL 4.

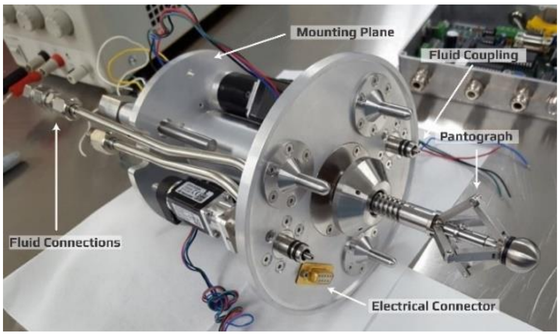

Figure 10 – ASSIST end-effector (active part)

The end-effector is foreseen to be attached to a robotic arm on the servicer S/C, which includes fluid and electrical connections, and a grasping mechanism which docks with the berthing fixture mounted on the client S/C.

The breadboard was used and validated in the scope of EROSS project, where it was completed with a dedicated SW component or API to automate ASSIST docking, refuelling and de-docking operations in compliance with ERGO framework.

4.5 ASSEMBLY WORKBENCH

The assembly workbenches are used as reference elements for the assembly operations. They are composed of an electronic box, an end effector to grab and position the parts that will be assembled and a deployment system used to position the end effector. There is two different workbenches, one to build the sub-reflectors and one to build the reflector assembly as depicted in Figure 11.

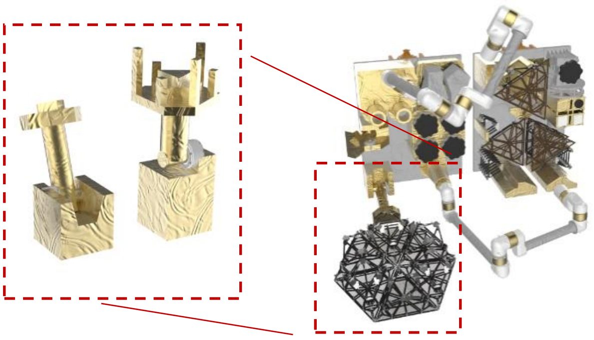

Figure 11 – Assembly workbench

The end effector is designed to precisely position the parts one from the other before assembly and also to grab the parts as a means to free the manipulator which will be able to perform assembly or other operations.

4.6 CUBESAT MODULES

Modularity and simplicity are key selling points for CubeSats in the commercial space market, which makes the nanosatellite standard a suitable choice for demonstrating in-orbit assembly and reconfiguration of spacecraft, where modularity is a must.

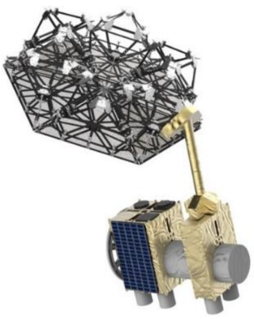

Figure 12 – Assembled CubeSat Configuration

In the PERIOD mission, a 12U (Figure 12) module will contain the core avionics necessary for any satellite, while a separate 6U module will contain the payload. The two modules will be attached together at the assembly workbench, and the connection between the modules will be established by the Standard Interconnects. The manufactured reflector dish is then attached to the payload module, completing the configuration.

4.7 ESROCOS

ESROCOS[3] is an open-source framework designed as an European Space RObot Control Operating System (ESRORCOS) for space robotics applications. ESROCOS provides this framework to assist in the development of flight software for space robots, providing adequate features and performance with space-grade Reliability, Availability, Maintainability and Safety (RAMS) properties.

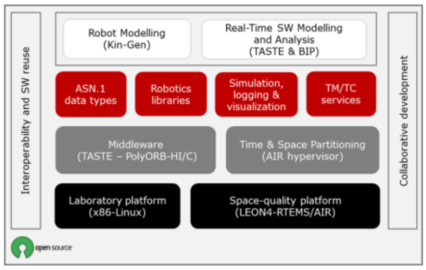

Figure 13 – The ESROCOS software architecture

ESROCOS supports a collaborative development approach based on component reusability. The framework was used and developed throughout multiple OG projects such as EROSS, PULSAR, MOSAR, ADE and PRO-ACT.

4.8 TASTE

The solution is based on the ESA ASSERT Set of Tools for Engineering (TASTE) toolset, a powerful toolchain that supports the creation of systems using formal models and automatic code generation. It makes the bridge between existing and mature technologies such as Simulink, SDL, ASN.1, C, Ada, and generates complete, homogeneous software-based systems that can be deployed on a physical target.

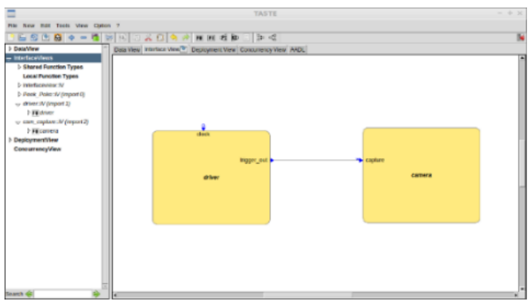

Figure 14 – Taste GUI

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[3] http://www.h2020-esrocos.eu

TASTE follows a Model Driven Engineering (MDE) approach for the specification of the implementation of the system functionality using different viewpoints, this approach allows different robotic software components to be combined to describe the different views of the OBSW, guaranteeing consistency.

4.9 ERGO

ERGO[4] stands for European Robotic Goal-Oriented autonomous controller, and it is a framework focused on providing autonomy and planning solutions suitable for single and collaborative space (orbital and planetary), and terrestrial robotic applications. ERGO autonomous framework is built on ESROCOS/TASTE frameworks, and its modular and flexibly designed components allow a friendly integration with other core building blocks (InFuse, I3DS), Standard Interconnects (SIROM, HOTDOCK), Refuelling Interfaces (ASSIST) and other robotics platforms, such as robotic arms with different DoF, and/or rovers with different locomotion systems (wheeled or legged).

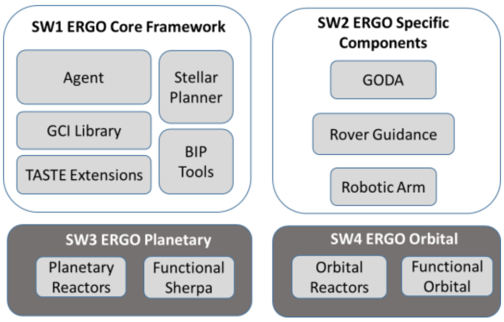

Figure 15 – ERGO framework SW packages

The framework has already been used, customised, and matured in multiple orbital and planetary space projects as EROSS, MOSAR, ADE and PRO-ACT.

5. CONCLUSION

This first In Orbit Demonstration (IOD) represents an important step for European space robotics. The low-cost approach allows a complex in-orbit demonstration without having to provide money for systems like a free-flying satellite. The demonstrated system architecture is impressive in that all European building blocks are used and combined in a functional and competitive system. Only the consideration on system level showed the need for development and harmonization of some of the components. This task was solved in PERIOD and will be demonstrated in the next phases first on the ground and later in orbit.

[4] https://www.h2020-ergo.eu

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