In-Orbit Demonstration of ISMA Robotic Capabilities to Pave the Way for a New Generation of Space Systems

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Abstract

When one thinks about how satellites and spacecraft are built today, the picture which immediately springs to mind is the large clean room, the heavy personnel needs, and the large launcher required to transport a volume-constrained payload to space. The PERIOD project seeks to disrupt the status quo by showing there is an alternative to the traditional approach of manufacturing, assembling and validating space hardware on-ground with direct in-orbit manufacturing and assembly using robotics, autonomy and modularity. The advantages are multiple. No more constraints on the overall volume and design of large-scale satellite antennas. Ample opportunities to construct larger space infrastructures such as modular space stations and lunar surface infrastructure. On top of this, the ISMA (In-Space Manufacturing and Assembly) technologies would allow for the upgrade and repair of existing spacecraft and satellites, thereby fostering the sustainable usage of space through plug and play modularity.

The ISMA industry can bring revolution to space market achieving a sustainable space ecosystem and offering new services. The PERIOD consortium is confident that a decade from now, considering a stepwise evolution, many different capabilities will be required. Large-antenna commercial satellites autonomously assembled in space will provide citizens with a wide range of services, and scientific satellites will allow us to see further into deep space than ever before. Payloads will be autonomously exchanged on standard reconfigurable satellites. Most satellites will be repaired, serviced or de-orbited in space, meaning that we will be able to better face the space debris issue. Advanced space robotics will be used for local and autonomously manufacturing and assembly on the space stations in LEO (Low Earth Orbit), lunar and mars orbits, and indeed on their surfaces. Even more remarkably, the same robotic technologies and autonomous industrial processes will be used for producing resources in space, even producing human organs for citizens on Earth.

This paper describes the results of the PERIOD project performing a phase A/B1 mission study and technology maturation activities aiming to prepare the paradigm shift for changing the way space systems are designed, built and operated, moving from mission-specific solutions to modular spacecraft optimised for the space environment.

Keywords: In-Space Assembly, In-Space Manufacturing, Refueling, Robotics, Autonomy, PERASPERA

Acronyms/Abbreviations

Cargo transfer bags	(CTBs)
In-Orbit Demonstration	(IOD)
In-Space Manufacturing and Assembly	(ISMA)
International Space Station	(ISS)
Low Earth Orbit	(LEO)
Mobile servicing system	(MSS)
Operational Grant	(OG)
On-Orbit Servicing	(OOS)
PERASPERA In-Orbit Demonstration	(PERIOD)
Robot control unit	(RCU)
Standard Interconnect	(SI)
Strategic Research Cluster	(SRC)
Telemetry / Telecommand	(TM/TC)
Data Handling System	(DHS)

1. Introduction

The idea of assembling or even manufacturing systems in orbit and putting them into operation is not new. In science fiction novels where mankind possesses the ability to travel the depths of space, it is a common assumption that the enabling systems are built and maintained this way because it is obviously a logical and necessary technological milestone to get to that stage of evolution. In fact, this practice has already been applied. For example, for one of the largest space ventures that mankind has accomplished together so far - the ISS. Individual modules, which were transported separately into orbit, were interconnected via standardized interfaces and put to service. However, this was not yet realized by autonomous robotic systems, but rather by astronauts, partly with support of remotely operated manipulator arms.

The need and also the advantages of these system and operations concepts are obvious if you take a closer look at the ISS example. Given the existing transport means, it is impossible to transport such a large structure in its assembled state into orbit in one piece. A modular design therefore provides the basis for integration in orbit. The modularity also allows the separate design, development and production of the various functional units by different partners and nations. Standardized interfaces allow for simplified assembly and also serve for cross-project system specification and harmonization. In addition, it opens up the possibility of future maintainability, upgradability and expandability of the facility by exchanging old or adding new modules.

Until now, this approach has only been used for very large, technically complex and expensive systems, always involving astronauts in the processes, which drives up safety requirements and costs. Of course, the approach also offers advantages for comparable smaller and less complex space systems such as satellites to e.g. extend their lifetime or to equip them with reflectors of theoretically unlimited size, which is currently not possible even with pre-assembled deployable reflector subsystems (as e.g. [1]). Another advantage that could come into play with such systems is the possibility of manufacturing structures in orbit, i.e., not having to design them to withstand launch loads when assembled. This means that the structures can be constructed with significantly less material and thus be lighter and take up less volume, which should reduce launch costs.

Blocking points for the methods used so far, especially for applicability for commercial applications, are the high costs and efforts associated in particular with the necessary operations of astronauts. The use of robots with high autonomy levels taking over the work previously performed by astronauts in orbit could resolve this situation and help to realize a new generation of space systems with enhanced performances and capabilities and to establish associated valuable business cases.

To achieve this, the necessary technologies must be developed, tested and demonstrated in representative scenarios in orbit to convince all stakeholders that the space industry is ready to offer the appropriate products and services. Therefore, the European Commission together with European national space agencies have established the Strategic Research Cluster (SRC) PERASPERA [2], which defines and implements a roadmap to first develop generic robotics and autonomy technology building blocks [3,4,5,6,7] to be tested in relevant application scenarios [8,9,10] in terrestrial demonstrations, ultimately leading to the definition and realization of an in-orbit demonstration (IOD).

PERIOD [11] is one operational grant (OG) of PERAPERA which aims at a Phase A/B1 mission study for the IOD and the further maturation and integration of the building blocks for the developed mission and system concept. The envisaged ambitious IOD was to lead to the manufacturing of a functioning satellite in an ‘orbital factory’ accommodated on the ISS Bartolomeo platform (see Figure 1) by 2026 with the objective to prove robotic technologies and operations to convince all stakeholders about the readiness of capabilities to make this vision reality.

After this introduction, the paper defines the envisaged applications and use-cases for the IOD, followed by a description of the key requirements. The mission definition and necessary operations are presented, followed by a description of the system concept and provided capabilities. The control software and main components are then presented, followed by a discussion of the PERASPERA building block maturation as well as system development activities. Finally, a conclusion and outlook are given.

Figure 1: Accomodation of the orbital factory on Bartolomeo for phase E of the IOD

2. Applications and Use-Cases

As of today, satellites are not designed for on-orbit servicing, and industry has yet to align on standards for attachment points, refuelling ports, and other servicing-oriented features which are needed to advance the market. Serviceable satellites will be supported by the development of the Standard Interconnects (SIs) within PERASPERA activities and a long-term servicing market could develop from 2030 onwards. More immediate mid-term applications of ISMA will be in the assembly of structures in orbit. The future space ecosystem can then capitalise on these applications which will enable the construction and maintenance of the future space infrastructure. Considering this, efforts should be focused on the critical infrastructure elements that will be necessary to grow the LEO and cislunar economy while maximizing European synergies, particularly between the EU and ESA. With the new validated capabilities, industry can take over with the proposition of new commercial services and applications in the domains of (1) manufacturing, servicing, and assembly of hardware in orbit, (2) building products in space for return to Earth, and (3) In-Situ Resource Utilization (ISRU). A clear focus on the technologies necessary for this will significantly increase the potential growth of the future space economy.

Based on these prospects and the strategic planning of the consortium partners, it was decided to focus in PERIOD on the following three use cases, with prioritization according to the numbering:

(1) Antenna reflector manufacturing (large structure), (2) satellite assembly, maintenance, upgrade and reconfiguration, (3) satellite attachment and refuelling

3. Key Requirements

The key requirements for the mission and system concept are derived from the EC call "H2020-SPACE-2018-2020, SPACE-27-TEC-2020, A: In-orbit Demonstrator Mission Study" and have been defined in the PERASPERA Project Support Activity (PSA) by representatives of all involved space agencies (see [2]). The aim is to demonstrate technologies, capabilities, and use cases developed or considered in previous OGs in particular, in an IOD and thus create the foundation for future commercial business cases.

Hence, the IOD, which should be planned to be performed in 2025, shall allow building confidence on the feasibility of business based OOS and ISMA with high visibility for the larger public. Use-cases shall relate to short to long term applications and the mission and system concept shall be in full scale and immediately transferable to relevant applications [8-10]. It shall implement autonomy capable to cope with a range of conditions representative of the uncertainty of a real mission. The system concept shall be based on the SRC PERSAPERA technologies [3-7] which have to be developed and assessed up to TRL5 within PERIOD and shall reach TRL 9 after execution of the IOD. The overall budget for the Mission (Phase A-F) is expected to stay within 50-100M€.

4. Mission and Operations

The PERIOD mission will seek to autonomously manufacture a satellite including the fabrication of an antenna reflector, assembly of the satellite components, their reconfiguration and subsequent inspection in a so-called 'orbital Factory'. For the purpose of the IOD, the factory will be attached to the Bartolomeo platform which is externally attached to the International Space Station on the European Columbus module. It provides all services not linked to the technology demonstration (i.e. cargo launch, installation and maintenance, power supply and communication to ground, orbit and attitude control). The factory will be delivered to orbit with a satellite and reflector kit, from which the parts and components will be extracted robotically and assembled using a manipulator system with two manipulator arms. Once the assembly operations are performed, a telecommunication test with ground will be done to verify the newly in-space-assembled spacecraft. The PERIOD mission also proposes to separate the satellite from the station and perform autonomous testing of the spacecraft.

The related in-space manufacturing and assembly capabilities and associated technologies include antenna reflector assembly, satellite assembly, satellite reconfiguration, satellite inspection, testing and decommissioning. The capabilities and technologies will be tested in different conditions to assess the performances and limitations of the system for future implementation of in-space services, manufacturing and assembly.

The system concept of the PERIOD mission relies on the use of the Bartolomeo platform which serves twelve payload slots each equipped with a GOLD-2 standard interface to attach elements and provide mechanical, power and data connectivity. This allows the PERIOD efforts to focus on compliance to the Bartolomeo platform and development of the demonstrator itself. However, it will also be ensured that the system concept and the operations to perform the IOD are compliant with ISS safety requirements.

In this way, the space segment of the PERIOD system will be composed of the Bartolomeo platform equipped with two out of three individual payload boxes at a time. The 'Factory Box' containing the orbital factory, the 'Satellite Kit Box' containing the satellite and reflector kit, and the 'Refuelling Box' containing a docking and refuelling experiment. The Columbus Control Center is the on-ground entity that that will support the PERIOD monitoring and commanding. It will forward TM/TC data from the PERIOD control and command centre via the Columbus module and BTL, to the PERIOD space segment.

The PERIOD mission phases are defined as follows (see also Figure 2):

1. **Launch** of the system in soft stowage, packed into cargo transfer bags (CTBs) wrapped with foil and foam and stabilized during launch with manual launch locks.
2. **Unpacking** of the PERIOD system by the ISS crew and removal of CTBs, foils, foams, and manual launch locks.
3. **Installation** of Factory Box and Satellite Kit Box on the Bartolomeo payload slots using the mobile servicing system (MSS, Canadarm2) and the ISS crew.
4. **Assembly of the reflector** in space using the PERIOD robotic manipulators in the Factory Box.

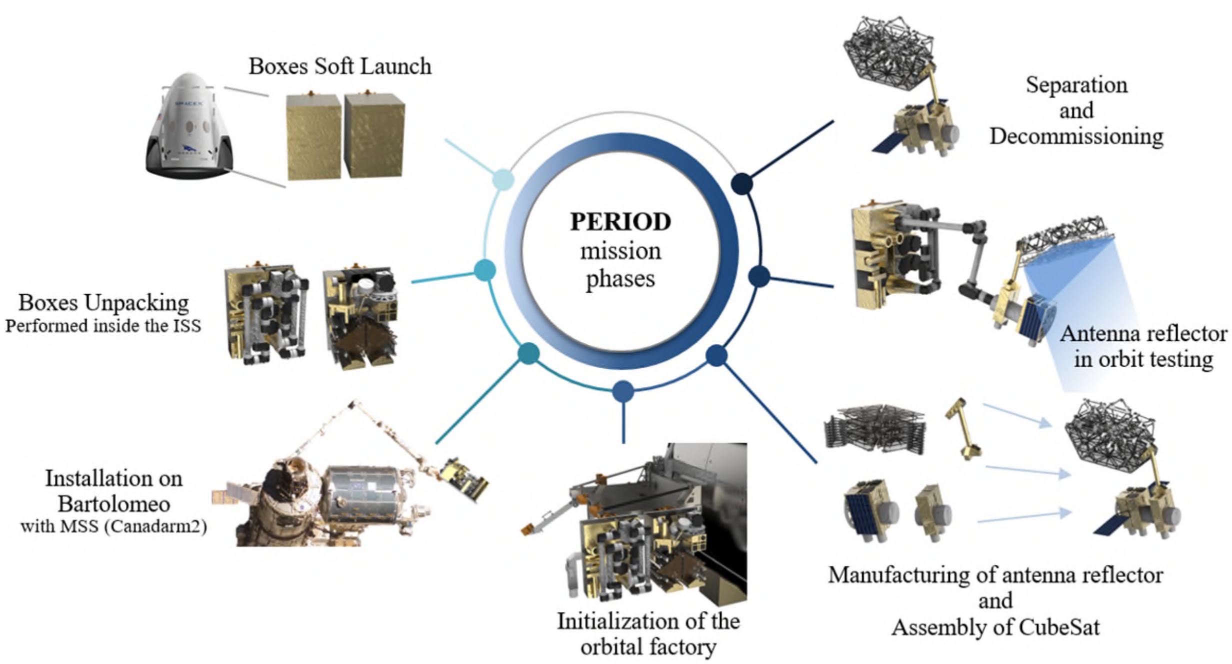

Figure 2: PERIOD mission phases

The reflector is made of generic elements stored in a way that optimises the volume in the Satellite Kit Box.

5. **Tuning** - The reflector design is compatible with Ka-Band telecommunication and is adjustable to correct assembly errors. The reflective surfaces are equipped with markers whereby the position is measured using photogrammetry in order to compute the correction needed and to be made by the manipulators.
6. **Modular system reconfiguration** - The satellite is composed of a core module and a payload module that are assembled using a Standard Interconnect, either HOTDOCK or SIROM.
7. **Assembly of the satellite** together with the reflector after which a final inspection is performed to measure the relative position between the two elements and to adjust it using a pointing mechanism if needed.
8. A **telecommunications test** with ground is perform by using the manipulators to track the ground station with the spacecraft attached to the end effector. The antenna performances and characteristics are verified.
9. **Robotic actuator swapping** demonstration is performed whereby a robotic actuator/joint along the robotic manipulator arm is removed and replaced by another to demonstrate arm maintenance operations.
10. **Release from ISS** - The spacecraft is launched into space and separated from the ISS/BTL in order to perform autonomous telecommunication tests.
11. A box exchange operation is performed between the Satellite Kit Box and the Refuelling Box in order to perform a **docking and refuelling operation** demonstration for test and validation of a docking and refuelling mechanism (ASSIST).
12. **Decommissioning** - Once the PERIOD mission is performed, the boxes are brought back into the ISS for decommissioning.

Mission phases 4-8 and 11 are the most relevant regarding the in-orbit demonstration of robotic capabilities. The defined sequence of operations is depicted in Figure 3. After initialization of the boxes, the manufacturing of the reflector antenna and the assembly of the CubeSat will be performed autonomously by a robotic system. The correct antenna function will be tested with an RF link to a ground station by positioning the whole assembled satellite with one factory manipulators. Finally, the assembled satellite will be deployed with a NanoRacks Kaber deployer and the MSS to perform its own LEO mission.

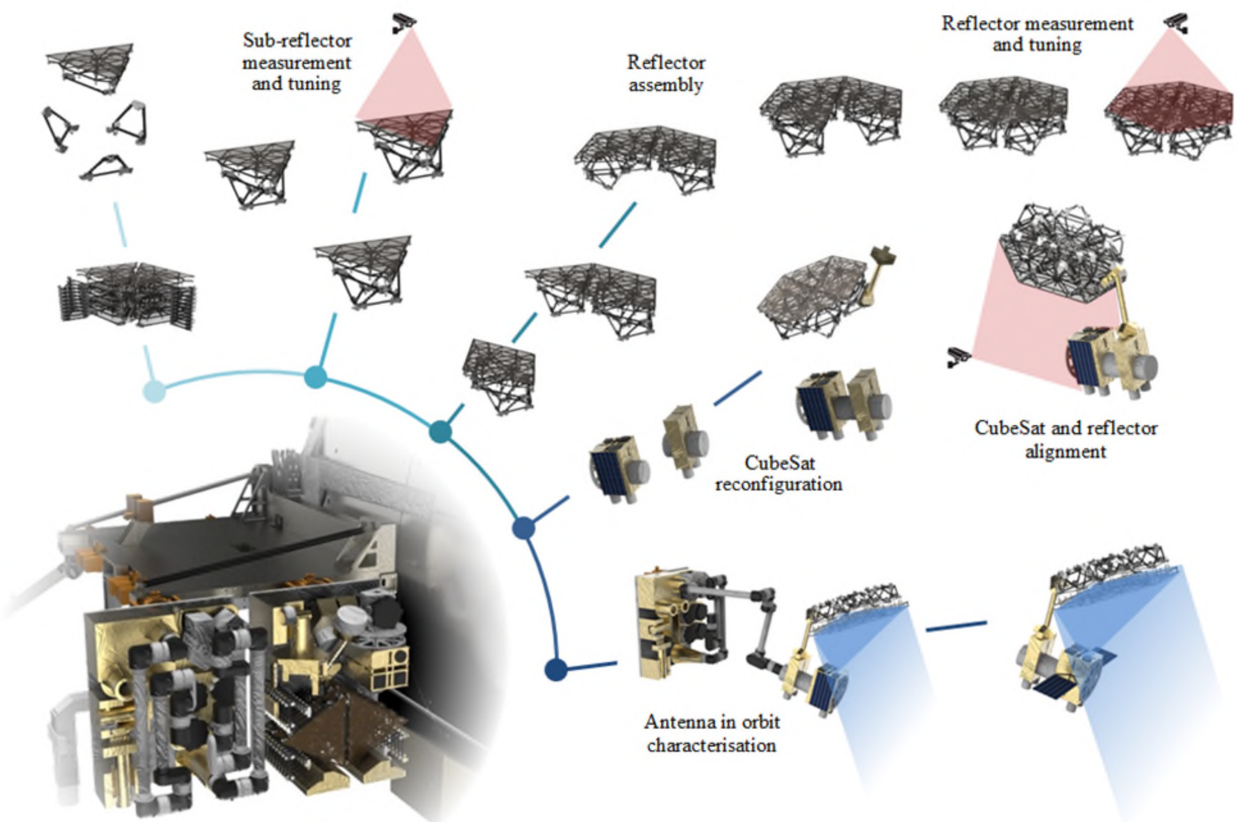

Figure 3: Reflector and CubeSat in orbit assembly and verification process

5. Systems and Capabilities

One objective of the PERIOD project is the demonstration of ISMA capabilities that can later be utilised for commercial products and services. To this end, the constituents of the PERIOD system are defined in a product-centric approach, identifying technologies that can also be re-used as self-standing products. This product approach was also at the core of the System of Interest definition. The orbital factory is composed of the following products (see Figure 4).

5.1 Robotic Factory

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 their end-effectors, a spare joint for the manipulators and a free manipulator slot to store parts of the manipulators during manipulator joint exchange operations.
- **Set of tools** that can be connected to the end-effector of a manipulator. The tools are designed using the same product approach with a Multi-Purpose Tool integrating the controller and actuator of the tool socket. The Multi-Purpose Tools are also equipped with cameras in order to perform the visual-based control during the assembly process thereby increasing the positioning accuracy. The cameras are also used to perform shape measurement (photogrammetry) of the reflector.
- **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 to perform workbench reconfiguration.

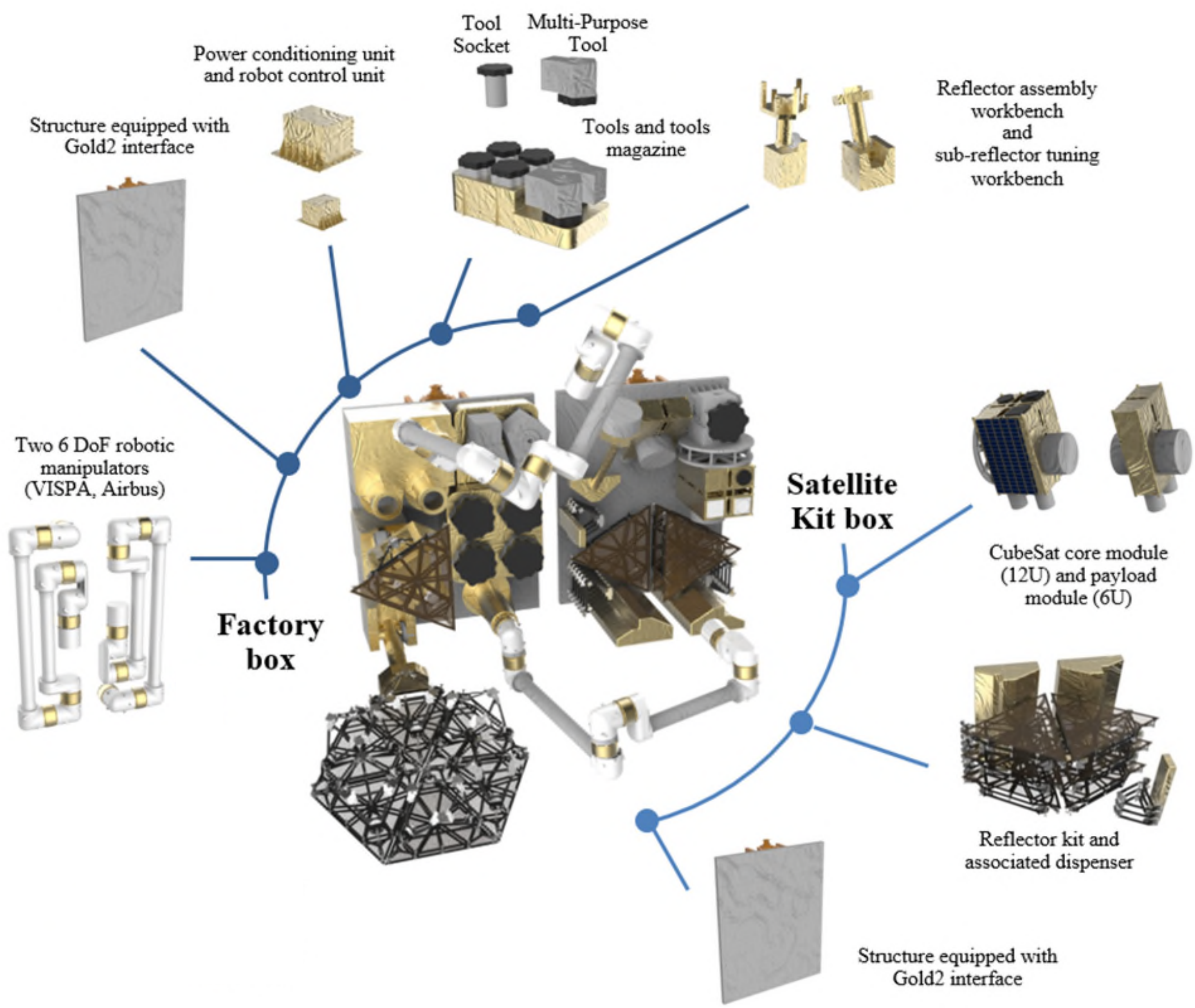

Figure 4: Product breakdown of the orbital factory

- **Power Conditioning Unit (PCU)** for power conversion and distribution.
- **Robot Control Unit (RCU)** for control and data processing running the **Control Software** to execute and monitor autonomous robotic operations (details see section 6.)

5.2 Satellite Kit

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) and associated **CubeSat payload module**. The two modules are equipped with standard interconnects to be able to connect them together and allow connection with the manipulators

5.3 Antenna Reflector

The antenna reflector, its design and related robotic manufacturing processes definition is a product in its own. The antenna reflector design is based on a modular approach. Indeed, the reflector is made of triangular shaped sub-reflectors assembled together in order to form a hexagonal shaped reflector. In the frame of the PERIOD project, the reflector is composed of 6 sub-reflectors in order to form a 0.75 m diameter reflector but the design has been made to be compatible with bigger reflector assembly. By adding additional sub-reflectors to the assembly, it's possible to create a bigger reflector.

In launch configuration, the reflector parts are stowed in the satellite kit box in order to optimize the launch volume and are then assembled in space. Each sub-reflector is composed of 4 elements (3 structural frame and 1 reflective surface).

The Sub-reflector reflective surface are tuneable in order to be compatible with other antenna geometry but also to correct the geometrical errors created during the assembly process. As the reflector is compatible with telecommunications up to Ka-Band, the reflective surface need have an RMS error lower than 0.2 mm. Thereby, the reflective surface is measured and tuned after the assembly of the sub-reflectors.

The reflector is fully passive and that all the assembly, measurement and tuning operations are performed by the robotic manipulators and dedicated actuators/tools. Indeed, the reflector is design for robot-based assembly and verification. Each part has been design to be grabbed, assembled, released and verified by the robotics manipulators. Dedicated interfaces has been design for assembly, tuning and grabbing operations.

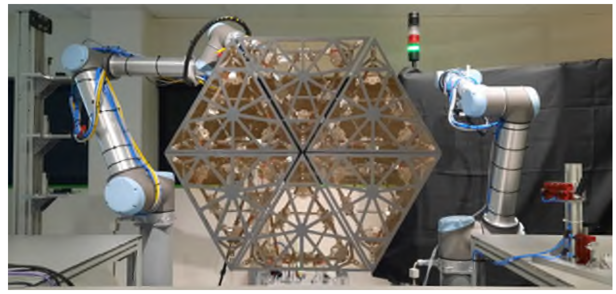

Figure 5: Antenna Reflector assembled by robots in the Airbus Defence and Space robotics lab in Toulouse

5.4 Modular Client Satellite

A modular client satellite is designed to facilitate robotic assembly and provide payload exchange capabilities to accommodate the ISMA demonstration. The design of the satellite developed in PERIOD also allows to connect and utilize the manufactured antenna reflector.

The client satellite is implemented using the CubeSat form factor, to take advantage of the relatively inexpensive flight-proven hardware that already exists. 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,

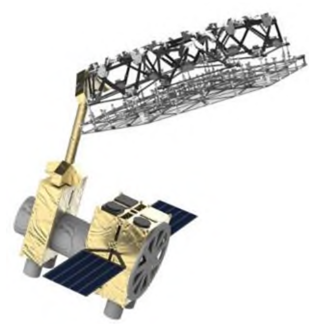

Figure 6: Assembled Client Satellite Configuration

For the PERIOD mission, a 12U core module will contain the avionics of the platform bus, while the payload is located in a separate 6U module. 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 (Figure 6).

While the SI's will facilitate the modularity, they are not necessarily designed with the CubeSat standard in mind. Some additional development will be needed to allow for the SI's to properly interface with the CubeSat structure and avionics.

One major challenge will be to appropriately size and configure the AOCS actuators to allow for the necessary attitude control of the platform during flight. The additional components assembled onto the client satellite will modify its physical characteristics, such as the Moment of Inertia, by a substantial amount, and must be considered during the design of the core module.

A physical distinction between a core set of avionics and attachable payloads is a natural evolution of the CubeSat philosophy and will allow for both more demanding missions to be launched at lower cost by including an in-orbit assembly mission phase, and extension of ongoing mission by allowing mid-flight upgrades. This functionality will readily expand mission capabilities for low-cost satellites, giving a major boost to innovation in Low Earth Orbit and beyond.

5.5 Standard Interconnects

The standard interconnects are key enablers for a modular design of spacecraft and ease flexible robotic handling of modules. They provide multifunctional intersection capabilities that allow e.g. modules or systems equipped with an SI to be interconnected mechanical, electrical (power and data) and thermal. In the example of the Factory in PERIOD, the idea is that 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 payload module providing a new function to the core module mechanically as well as transmit electrical power and data for supply and control. For the PERIOD scenario, two different standard interconnects, SIROM and HOTDOCK, developed and utilized in previous PERASPERA OGs, and described in the following sections, have been considered. To determine the most suitable interface for defined use-cases, these two SIs were tested and compared together with a third potential option iSSI® [12] in the so-called SI benchmarking. The objective is to give a recommendation for one of these three standard interconnects (see section 5.5.3).

5.5.1 SIROM

SIROM [7] is designed as an androgynous interface allowing easy mating/demating with other SIROMs (see Figure 7). 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, which gives information once two SIROMs are within the latching capture range. Once mechanically latched, SIROM deploys its connector board to establish a physical plug for data, electrical power transmission and fluid transmission (optionally) [13].

Figure 7: Active SIROM (left), Passive SIROM (right). PERIOD benchmarking versions

5.5.2 HOTDOCK

HOTDOCK [14] 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.

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.

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

5.5.3 SI Benchmark

The main objectives of the SI benchmark was to evaluate all three involved SIs (HOTDOCK, SIROM and iSSI®) with respect to the demonstration scenario and associated requirements. Furthermore to provide feedback on how to further improve the current version of the SIs for an orbital mission, such as that conceived by the PERIOD project and in addition a recommendation of one Standard Interconnect solution was foreseen for the phase B2 development.

For the definition of the baseline of the SI benchmarking the ECSS-E-HB-11A handbook and related standards were used as guidelines. Additional requirements to be considered by the benchmarking came from the mission scenario of the PERIOD project.

The SI benchmark test procedure was divided into two main areas: electrical and mechanical tests. The electrical tests aimed to analyse the application-oriented functioning of SIs, focusing on electrical aspects for data and power transmission [15]. The mechanical tests focused on the values supplied by the SI providers and also from the project requirements, such as the dimensions and weights of the respective SIs, as well as the function of the mechanical locking mechanism and the misalignments that can be compensated for during a docking operation [16].

Two pairs of each SI were tested. One pair consisted of one active and one passive SI. Since the SIs are not directly comparable to each other, due to their different functionalities and components, an ontology was developed that allowed an evaluation by weighting to be performed. A first analysis showed that each SI is applicable, provided that it is adapted according to the required application scenario. For use in orbital mission scenarios, all three SIs are applicable, provided the installed components are space qualified.

5.6 Refuelling Experiment

The refuelling & attachment experiment will be demonstrated utilizing the Factory Box and the Refuelling Box. The objective of the experiment is to demonstrate the fluid transfer capability in orbit using the ASSIST technology. This demonstration will also validate the attachment capability of the ASSIST device during berthing operations and fluid transfer. Standard interface attachment and docking capability under free flying conditions could be also validated taking advantage of the experiment set-up shown in Figure 9.

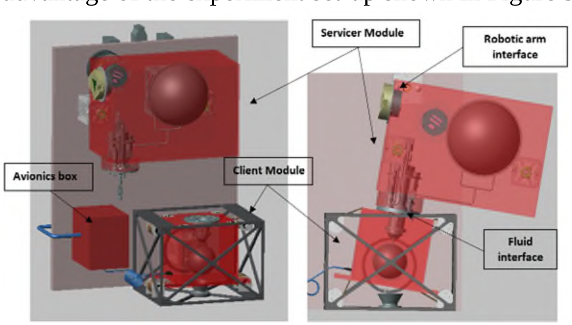

Figure 9: Refuelling experiment concept

5.6.1 Refuelling Interface

ASSIST [17] is an ESA initiative towards standardization for on-orbit servicing of satellites refuelling and docking; covering the grasping, fuel transfer and data exchange to support the refuelling and docking operations (see Figure 10). A first version of ASSIST provided a full-scale mechanical model manufactured to test the mating, fuel and data transfer operations. The breadboard model reached a TRL4 in in the frame of ESA's COMRADE and EROSS PERASPERA projects.

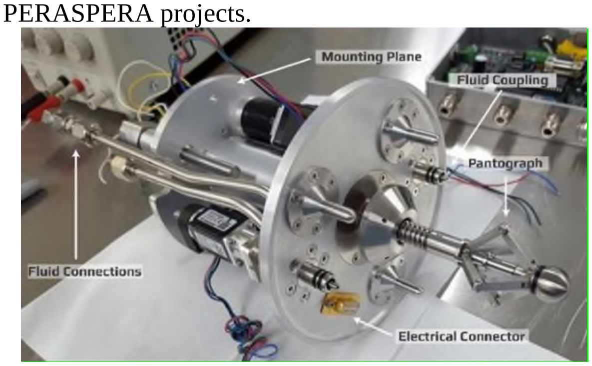

Figure 10: ASSIST end-effector (active part)

The ASSIST refuelling scenario foresees a client spacecraft prepared with external and internal refuelling provisions (ASSIST berthing fixture), that is refuelled by a servicer spacecraft equipped with the ASSIST end-effector and, potentially, with a robotic device. It supports docking, mating, fluid and electrical connections. Its grasping mechanism docks with the berthing fixture mounted on the client S/C.

The breadboard was used, extended 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 un-docking operations in compliance with ERGO framework.

5.6.2 Free-Floating Client

The set-up (see Figure 9) will consist of two independent modules, servicer and client, that will include all the components required for the fluid transfer (tanks, pipes, valves, sensors, etc.) and attachment devices (ASSIST and SI). The client module will be fixed into the BTL platform by a centring mechanism that allows either to keep the client in a fixed position in the middle of its cage or in a free floating condition where the module is supported by a low stiffness spring system and can drift away. This way, it will be possible to perform the tests from the simpler (fixed configuration) to the more complex free floating condition. The experiments will be repeated at least three times, from ASSIST docking, fluid transfer to ASSIST undocking.

Once the attachment proximity parameters will be in line with operation requirements, the client module will be released from the hard mechanical attachment (keeping safety aspects) and the robotic arm, visual servoing, software algorithms and interface devices functionalities will need to guarantee the modules attachment.

6. Control

Autonomous on-board robot control, in particular for manufacturing and assembly requiring adaptive behavior to cope with uncertainties, is quite demanding, both in terms of algorithm complexity and processing performance to provide the needed sensing, planning and acting capabilities. Important software packages (PERASPERA Building Blocks) have been established in previous OGs (sections 6.2 - 6.4):

- 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 goal-oriented framework (ERGO) implements the planning, acting and monitoring capabilities of the factory.
- Sensor data fusion framework (Infuse) implements the perception capabilities of the factory.

In PERIOD, they were reviewed w.r.t. the demonstration needs, parameterized, adapted, and ported to the necessary extend to achieve the required capabilities and performance when implemented on the target avionics, to achieve TRL 5 for the defined mission and system concept.

As RCU on the space segment, initially a LEON4 based on-board computer was foreseen as baseline. Due to the exotic SPARC processor architecture porting of fundamental software libraries widely used for realization of robotic applications (e.g. for computer vision and motion planning) would have been required. A RCU trade-off was performed in the project also considering UltraScale+ (precursor to ongoing developments of NGUltra, e.g. DAHLIA) as well as Intel Atom based platforms. Finally, a ruggedized PC104 Intel Atom based system called e.Cube, which is already in use on Bartolomeo as Data Handling System (DHS), was selected. The widely used processor architecture comes along with extensive support and reduced porting effort. Interfaces for connecting the peripherals can be realized flexibly with a stack of existing PC-104 board interface cards. In addition, based on the experience of using the e.Cube as DHS on Bartolomeo, it was decided not to use RTEMS as the operating system, as originally planned, but to use a long term support release of Ubuntu. For the expected control frequencies real-time capabilities can be provided by the default scheduler, if higher frequencies were required real-time patches are available for the Kernel as well. Another concern on ISS is the needed provision of an anti-virus tool, which is available for Ubuntu but remains an unsolved issue for RTEMS.

6.1 Software Architecture and Shared Autonomy

The software architecture integrates the required components of the different SRC software building blocks (ESROCOS, ERGO, InFuse and I3DS) and foresees a distributed deployment with interfacing between ground and the space segment (see Figure 11). 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 its final 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. Stellar mission planner and Robotic Arm Motion Planner) and pose-estimation of InFuse are foreseen to be instantiated within a TASTE/ESROCOS deployment only on-ground.

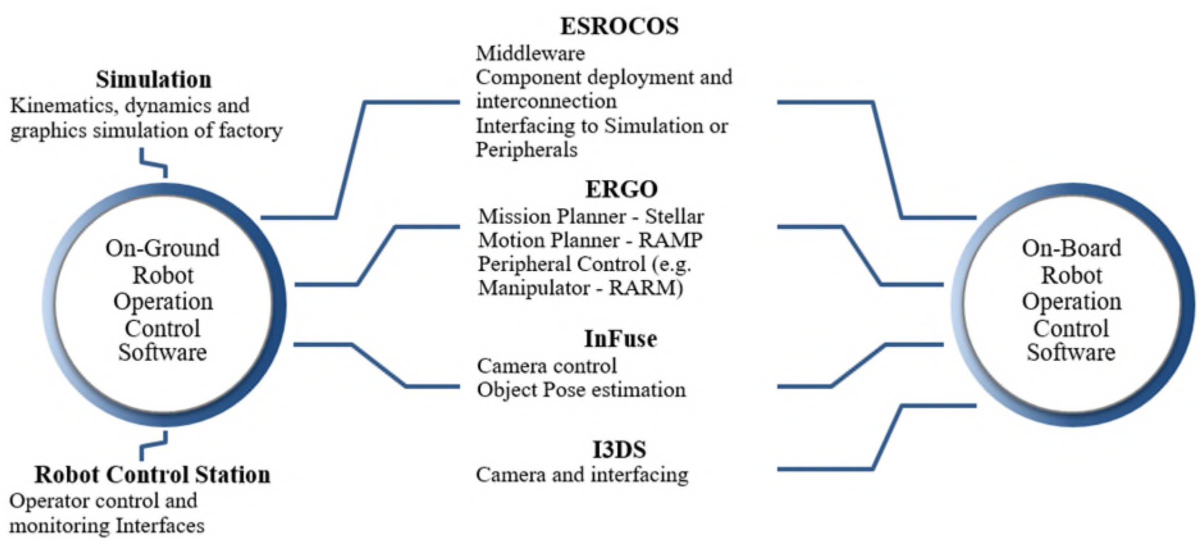

Figure 11: Deployment of software components

Whereas instances of the ERGO Agent components required for 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 ECSS autonomy level of E3 will be achieved on-board and E4 on-ground with the option to shift components running on-ground to the TASTE/ESROCOS deployment of the space segment later in Phase D to potentially achieve on-board autonomy level E4.

6.2 Robot Operating System

ESROCOS [3] is an open-source framework [18] designed as a European Space RObot Control Operating System (ESROCOS) 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 (see Figure 12).

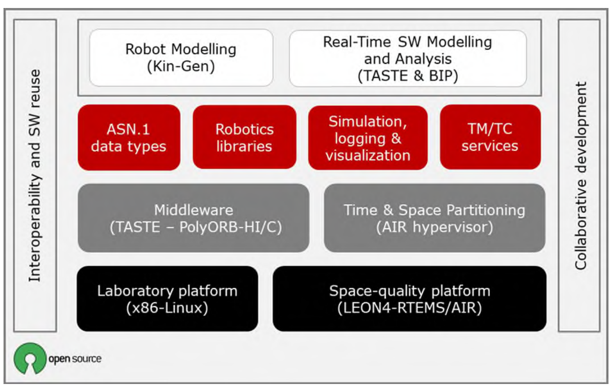

Figure 12: The ESROCOS software architecture

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.

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 are deployed on different physical targets transparently.

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.

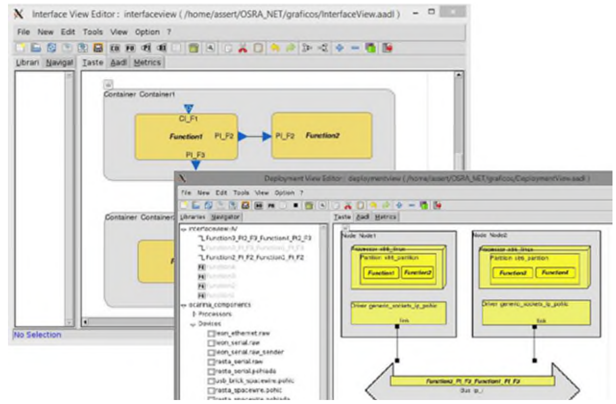
Figure 13: Taste GUI

6.3 Autonomy Control System

ERGO [4] stands for European Robotic Goal-Oriented autonomous controller, and it is a framework focused on providing E1-E4 ECSS autonomy levels for planning, execution, monitoring and control solutions suitable for single and collaborative (multi-robot/rovers) space (orbital and planetary), and terrestrial robotic applications. ERGO autonomous goal-oriented framework [19] 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).

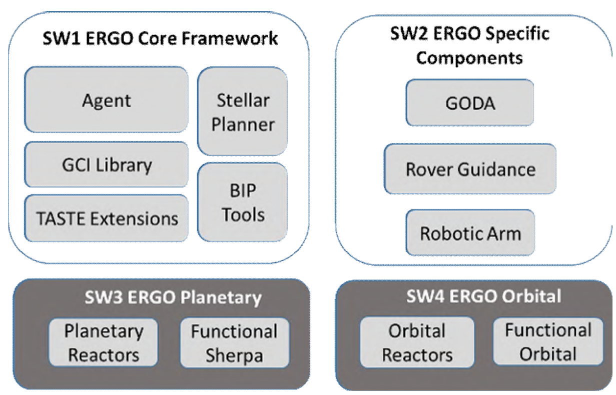

Figure 14: ERGO framework SW packages

ERGO framework is mainly composed by two different parts:

1. ERGO Agent; composed by a main controller and a set of deliberative, reactive and executive reactors responsible to decompose high level goals in simpler goals or tasks, execute and monitor the state machines of the different peripherals being controlled on each tick (|~ 1 second, but configurable). The Agent sends goals to the Functional Layer components (implemented as

TASTE functions) and receives observation (peripheral and/or subsystems feedback) from the last.

2. ERGO Functional Layer; implementing the commanding and monitoring at low level of the hardware components or peripherals being controlled by the Agent. It sends observations (peripheral and/or subsystem feedback) to the Agent and receives goals from the Agent.

The framework has already been used, customised, and matured in multiple orbital and planetary space projects as EROSS, MOSAR, ADE and PRO-ACT multi-robot/agent project allowing the coordination, collaboration and cooperation of a fleet of rovers.

6.4 Perception and Sensor Data Fusion

Two space frameworks have been used as building blocks for the perception capabilities: I3DS and InFuse [20]. The former one, I3DS (Integrated 3D Sensors suite), is a generic and modular system that answers the needs of near-future space exploration missions by integrating sensors and illumination devices in a coherent architecture as inter-changeable building blocks. The latter one, InFuse, provides a common framework of Data Fusion for Space Robotics with multiple Computer Vision algorithms and strategies. As explained before, these frameworks are seamlessly integrated with ESROCOS, ERGO and between each other.

A Marker Detection approach was selected as baseline for this project due to its robustness, accuracy, scalability, flexibility and simplicity. A set of ARUCO markers were used to unequivocally distinguish different references and determine their relative position and orientation to the camera.

Different tests were carried out to validate the accuracy and performance of the algorithms with the real camera and the synthetically generated datasets from the simulations.

In order to test the perception capabilities, a set of synthetic but realistic images are firstly generated by simulation means. These virtual environments include different versions of the Ground and Flight System setups that replicate the expected real conditions as accurately as possible. These simulations have been developed using Unreal Engine 5 (https://www.unrealengine.com/) and applying realistic physics, collisions, animations, textures, illuminations and a model of the camera and lens.

Results with the Marker Detection approach showed position errors below 1% for the 60% of images, and below 2% for the 85% of images relative to the distance to the camera. Orientation errors were below 0.2 degrees in average for all the dataset. Such errors are below the form-fit guidance tolerances of the Standard Interconnects, like HOTDOCK, that has a ±15mm-translational tolerance and ±10-degree tolerance. A study of the camera resolution, performance and marker sizes was also performed concluding that small markers can also be detected when placed in thin structures and in real-time with the given baseline distances.

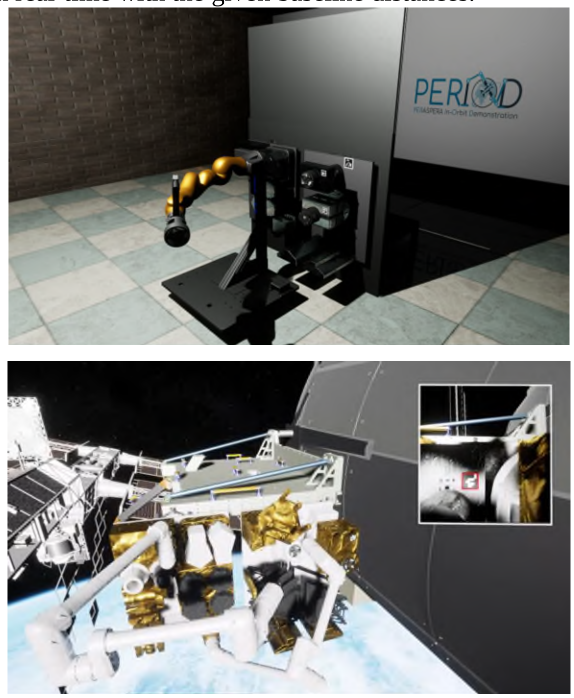

Figure 15: Simulation environment for the Breadboard demonstration (top) and the Flight System (bottom) to generate synthetic datasets for perception capabilities.

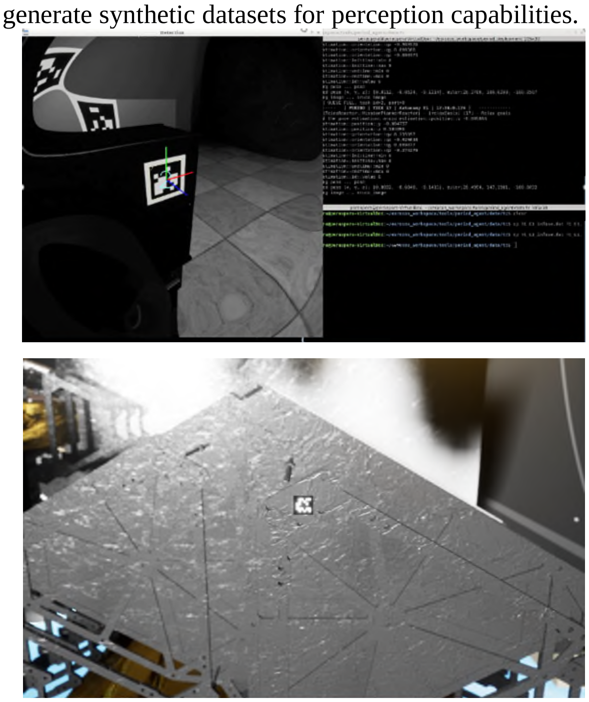

Figure 16: Results of the Marker Detection (InFuse and I3DS) using synthetically generated images (top) and study of the marker size for challenging parts (bottom).

7. Technology Maturation & Demonstration

In PERIOD an integrated proof-of-concept is implemented and performed in parallel to the mission study. It was planned to implement incremental development and validation loops of the technologies to get an early feedback on the system and component performances. To this aim it was foreseen to implement a breadboard for testing the assembly of satellite components. The breadboard will integrate the SRC building blocks ESROCOS, ERGO, InFuse, I3DS and Standard Interconnects in the existing Airbus Defence and Space 'Robotic In-Space Manufacturing & Assembly Testbed' (RISMAT, see Figure 17), already equipped with an industrial manipulator and to be extended with a representative RCU. This allows to test, validate and demonstrate the hardware and software interfaces and the interaction between the selected and matured components in a relevant operation scenario which will allow to achieve TRL5 with all SRC building blocks and provide very valuable information for preparing the phase B2 and C development along with the definition of the development and verification logic and for de-risking the overall development.

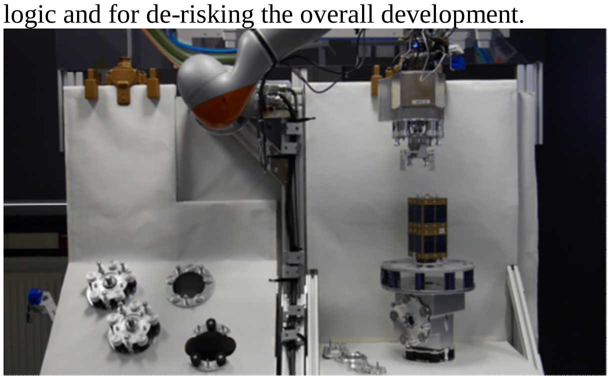

Figure 17: Robotic In-Space Manufacturing & Assembly Testbed (RISMAT)

The prepared development plan for Phase B2/C is articulated around two different factory models (see Figure 18). During Phase B2 an EM-based factory will be manufactured with a mechanical ground structure and equipped with Engineering Models (EM) and Breadboards (BB) equipment representative of the mechanical, power and data interfaces. The EM-based factory will be used for functional tests of the equipment, interface tests, software integration and testing, training of the teams and to perform reduced operational testing. In parallel, BB of the critical equipment not yet ready to be integrated in the EM-based factory will be manufactured and functionally tested. The equipment BB will take advantage of having mock-ups (representative of the interfaces) integrated in the factory to also check the constraints linked to the system. This model philosophy allows to de-risk early in the project both the factory system and also the functions of the equipment even if all the equipment are not at the same maturity level.

The Phase C will be dedicated to the Engineering Qualification Model (EQM)-based factory that will be equipped with EQM equipment. Each equipment will go through environmental, interface and functional testing before integration into the EQM-based factory made of the Factory Box and the Satellite Kit Box. The factory and satellite kit boxes will be tested for vibration and EMC with the arms and CubeSat inside to validate secondary structures design and the launch locks. The two boxes will be then integrated in a Bartolomeo-like structure in order to start the operational testing. For operational testing, first the reflector manufacturing and CubeSat assembly and measurement test will be performed under representative lighting environment in a clean room, followed by tests of critical operations in a thermal chamber with representative temperatures.

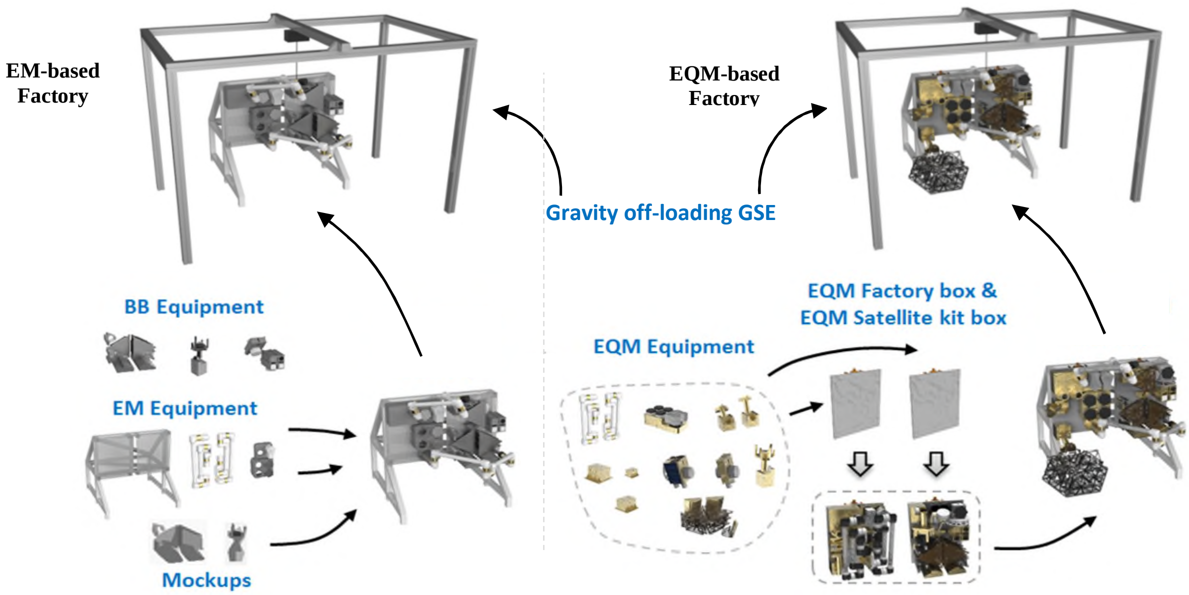

Figure 18: Model philosophy and development models

8. Conclusion & Outlook

In the Phase A/B1 study performed in PERIOD the most valuable ISMA and OOS applications and use-cases for the consortium were identified and mission and system concepts for an IOD to test and validate the needed robotics technologies and capabilities to perform the related operations and processes were defined. Particularly challenging were the given time and cost targets. According to the generated planning they can be met, partly due to the use of Bartolomeo as demonstration platform and the existing logistics and infrastructure provided by it. Direct transferability to a commercial application is possible to limited extent, as changes to the accommodation of the orbital factory will be necessary in order to use it on a different platform. For this, emphasis was placed on modular design and wide-ranging compatibility of the external interface.

Technology maturation activities to achieve TRL5 for all SRC building blocks for the defined mission and system concepts are currently in progress. The development and verification logic to achieve TRL6 on system level are defined. Unfortunately, PERIOD will be discontinued as the PERIOD consortium was not selected for the phase B2/C. Nevertheless, the partners of the consortium will continue developing the ISMA capabilities to bring the European industry in a competitive position and to allow Europe to be independent for the deployment and operations of the future space infrastructure.

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References

[1] M. W. Thomson, „The AstroMesh Deployable Reflector“, IUTAM-IASS Symposium on Deployable Structures, 6-9 September 1998

[2] H2020 PERASPERA, https://www.h2020-peraspera.eu/, (accessed 19.08.2022)

[3] European Space Robotics Control and Operating System (ESROCOS), https://www.h2020-esrocos.eu/, (accessed 19.08.2022)

[4] European Goal-Oriented Autonomous Controller (ERGO), https://www.h2020-ergo.eu/, (accessed 19.08.2022)

[5] InFuse - Data Fusion for Space Robotics, https://www.h2020-infuse.eu/, (accessed 19.08.2022)

[6] What's I3DS, https://eross-h2020.eu/i3ds/, (accessed 19.08.2022)

[7] Standard Interface for Robotic Manipulation of Payloads in Future Space Missions (SIROM), http://www.h2020-sirom.eu/, (accessed 19.08.2022)

[8] EROSS - European Robotic Orbital Support Services, https://eross-h2020.eu/, (accessed 19.08.2022)

[9] PULSAR - H2020 Prototype for an Ultra Large Structure Assembly Robot, https://www.h2020-pulsar.eu/, (accessed 19.08.2022)

[10] MOSAR - MOdular Spacecraft Assembly and Reconfiguration, https://www.h2020-mosar.eu/, (accessed 19.08.2022)

[11] PERIOD H2020 project, https://period-h2020.eu/, (accessed 19.08.2022)

[12] iSSI® – intelligent Space System Interface, https://www.iboss.space/products/, (accessed 19.08.2022)

[13] G. Guerra et al., "Development of a robotic Fluid Transfer interface based on RIDER connector", 16th Symposium on advanced space technologies in robotics and automation (ASTRA), Noordwijk, 2022.

[14] P. Letier et al., “HOTDOCK: Design and Validation of a New Generation of Standard Robotic Interface for On-Orbit Servicing”, 71st International Astronautical Congress, IAC 2020

[15] M. Yueksel et al., “A Methodology for Electromechanical Evaluation of Multifunctional Interconnects for On-Orbit Servicing Demonstration”, 16th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA), Noordwijk, 2022.

[16] W. Brinkmann et al., “A Standard Interconnect Benchmark for a European In-orbit Services, Manufacturing and Assembly (ISMA) Demonstrator”, 73rd International Astronautical Congress (IAC), Paris, 2022

[17] A. Medina et al., “Towards a standardized grasping and refuelling on-orbit servicing for geo spacecraft”, Acta Astronautica. 134, 2017.

[18] M. Munoz Aracon et al., “ESROCOS: Development and Validation of a Space Robotics Framework”, 15th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA), Noordwijk, 2019.

[19] J. Ocon et al., “ERGO: A Framework for the Development of Autonomous Robots”, 14th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA), Noordwijk, 2017

[20] S. Govindaraj et al. “InFuse: a comprehensive data fusion framework for data fusion in space robotics”, 14th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA), Noordwijk, 2017