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PERIOD – PERASPERA In-Orbit Demonstration toward the transition into the in-space services, assembly and manufacturing paradigm

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Abstract. Space robotics technologies are maturing, bringing new capabilities for In-orbit Services, Manufacturing and Assembly (ISMA). These capabilities will generate on-orbit services improving the orbital infrastructure, creating in turn a very promising business opportunity in terms of market volume. The establishment of a European capacity is necessary for building this new space infrastructure and to capture a fair part of this market. The concrete objectives of the PERIOD project are focusing on the main levers to generate the capabilities, which are the further maturation of the space robotics technologies and the definition of an in-orbit demonstration to be implemented as early as 2026. In the frame of the PERASPERA Strategic Research Cluster (SRC), key enabling products have been selected for technology

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maturation aiming at an increased technology readiness level (TRL). In support of the PERIOD activities, ESROCOS, ERGO and InFuse will be developed to TRL5 after an alignment of their perimeter to the demonstration objectives. The Standard Interconnects (SI), already at TRL5 at project start, will be tested in a benchmark for evaluating their performance. These SRC building blocks will be integrated in a breadboard at Airbus for supporting the system definition work. The PERIOD Consortium bringing together the competencies of Airbus Defence and Space, DFKI, EASN-TIS, GMV, ISISPACE, SENER Aerospacial and Space Application Services is proposing a very ambitious demonstration scenario and Factory concept. A satellite will be manufactured in an Orbital Factory to be designed in the study at SRR level and injected in LEO for operations. The manufacturing includes the fabrication of an antenna, the assembly of the satellite components and its reconfiguration and inspection in the Factory. Throughout the demonstration mission, the PERIOD facility will be upgraded to extend the level of capability validation from assembly and manufacturing of structures to attachment and refuelling experiments. Dissemination activities will maximize the impact of the project toward the Space Community. This demonstration covers the short and mid-to-long term ISMA business cases and will support the transition into the in-space services, assembly and manufacturing paradigm.

1. Introduction

Space robotics technologies are maturing, bringing new capabilities for In-orbit Services, Manufacturing and Assembly (ISMA). These capabilities will generate on-orbit services improving the orbital infrastructure, creating in turn a very promising business opportunity in terms of market volume. The establishment of a European capacity is necessary for building this new space infrastructure and to capture a fair part of this market. The concrete objectives of the PERIOD project are focusing on the main aspects to generate the capabilities, which are the further maturation of the space robotics technologies and the definition of an in-orbit demonstration to be implemented as early as 2026. This paper will describe from different viewpoints the high-level mission and system concept which integrates the identified ISMA capabilities as well as the robotics technologies in development.

2. ISMA market context

The ISMA market is still perceived as a very debuting market requiring real efforts, especially on demonstrations and use cases. On global trend analysis in-space servicing is on the short-term more related to inspection and life extension. Then, upgrade and repair activities will include in-space assembly and replacement of payloads' modules. Future steps can include on-demand manufacturing of spare parts for a servicing purpose [1].

From the understanding of the ISMA context and challenges the mission statement must consider the following aspects and objectives:

- Multiple new business cases and market opportunities reflected by the paradigm shift from Earth-based manufacturing (mission-specific solutions not optimized for the space environment) to space-based manufacturing (flexible spacecraft optimized for the space environment).
- Increase the viability of the demonstrator by providing rapid and low-cost upgrade capabilities to cope with the ISMA market orientation uncertainty.
- Characteristics of new space systems like higher value, higher capacities and higher resilience at lower costs.
- A qualitative and quantitative evaluation of the economical, technical, scientific and performance-related impact and benefits of standardized technologies, in order to tangibly contribute toward emerging regulations governing the commercial use of such technologies in space.

To unleash the full ISMA potential, 5 key enablers must be unlocked by the mission, going from customer awareness and transparency to technological and financial feasibility, regulations and investments:

- Technological feasibility and representative system demonstrations.

- Customer awareness on ISMA and its benefits.
- Transparency towards customers on risks and mitigations.
- Established standards & regulations for in-space activities.
- Accurate business cases and associated profitability.

3. Demonstration mission definition

3.1. Mission statement

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.
This mission statement is aligned on the goal to prepare the paradigm shift for changing the way space systems are designed, built and operated.

3.2. ISMA capabilities

The PERIOD demonstration will take place in a larger ISMA context introduced in section 2. The basis for the establishment of ISMA capabilities is the maturation of the underlying space robotic technologies and the alignment of these technologies on the specific needs of the in-orbit demonstration. A representative in-orbit demonstration mission is being defined in the PERIOD project based on the mission needs to validate the SRC (Strategic Research Cluster) developments for the purpose of simultaneously satisfying short-term (i.e. on-orbit inspection, reconfiguration, refueling) and mid-to-long-term (i.e. on-orbit assembly and manufacturing) business cases to be connected into the single PERIOD demonstrator. Following ISMA capabilities will be demonstrated in the PERIOD orbital Factory:

- Assembly of an antenna reflector,
- Assembly of a complete satellite from building blocks equipped with SI including verification,
- Reconfiguration of the satellite payload for system upgrade,
- Inspection of the assembled satellite and
- Refuelling with coupling between servicer and client mock-ups.

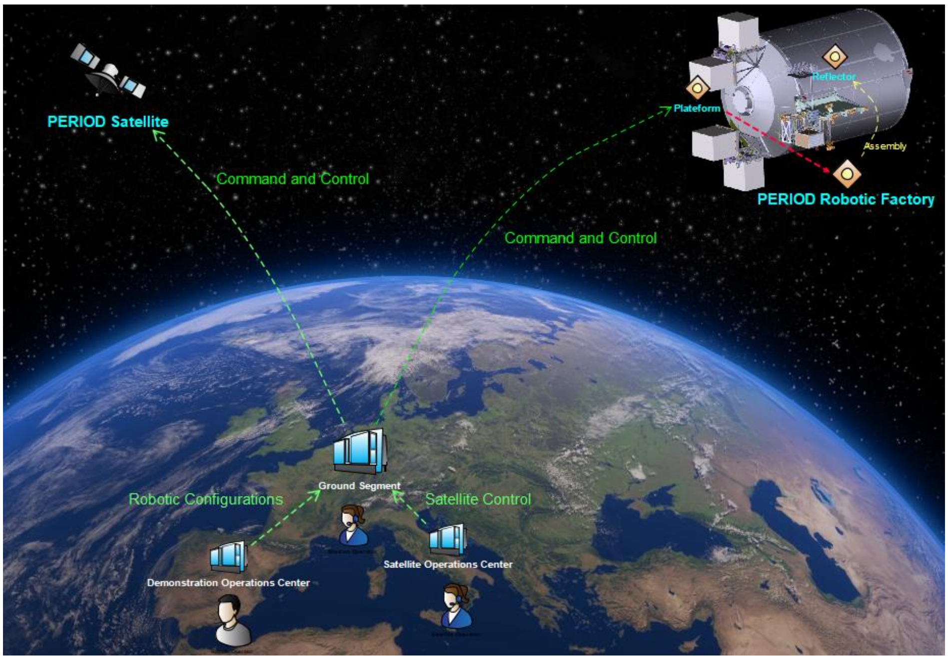
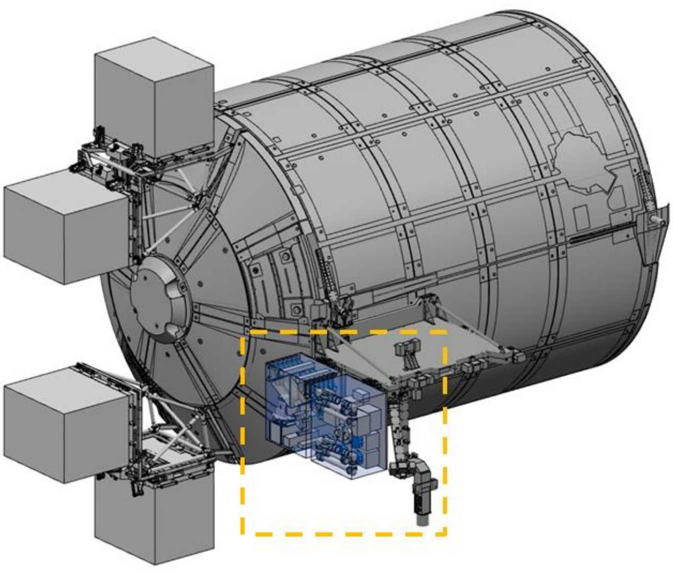


Figure 1. High level operational concept for LEO or GEO operations.

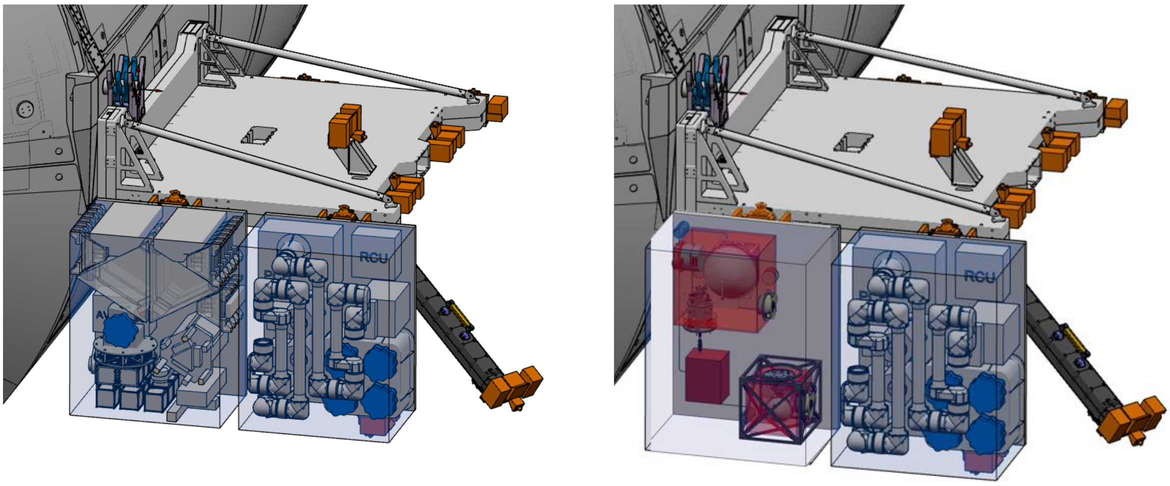
3.3. High level mission concept
The high-level operational concept of the proposed mission is depicted in Figure 1. The first part of the demonstration will take place on the Bartolomeo commercial platform accommodated on the ISS while in the second part the PERIOD satellite will be operated as a standalone system after its assembly in the factory and release from the ISS. The mission architecture is essentially made of a ground segment for managing the operations in terms of 'command and control' connected to the in-orbit robotic facility performing either servicing, assembly or manufacturing. The ground segment is also connected to the customer operations center when the PERIOD satellite is serviced. The orbital Factory will be automated to the maximum extent to achieve cost efficient operations.

4. System baseline definition
Among the ISMA challenges one is related to some uncertainties in the evolution of the ISMA market due to decreasing launch costs, lack of regulations (especially w.r.t. dual use) and the shaping of the commercial market w.r.t. GEO systems and LEO constellations. This uncertainty could mean that the demonstration defined today could become partly obsolete at the time of the demonstration. To mitigate this, a demonstration concept capable to be adapted late in the development cycle is required.
To this aim, the system concept of the Factory is based on modularity and consists of 2 configurations. Figure 2 depicts the Bartolomeo platform based on 2 slots and a Ground Control and Command system.

- One slot for the **Factory** which accommodates the robotic arms, the tools, the tool magazine, the avionics and the structure. This is the main unit for performing the robotic operations (assembly, reconfiguration, inspection...) but also calibration & verification.
- One slot able to manage 2 different configurations by exchanging two receiving service boxes to change the focus of the demonstration from assembly to refueling :
  - Configuration 1 for Satellite Assembly integrating the **Satellite Kit Box**, where all the satellites pieces of the reflector and the satellite body and payloads are stored before their assembly.
  - Configuration 2 for Refueling & Coupling integrating the **Refueling Box** providing both the fuel depot as well as an empty reservoir to receive the propellant. The reservoir will be free floating in space within its permitted envelope but securely attached to PERIOD Refueling Box. In order to initiate the fuel transfer, the servicer mock-up will be attached to the client mock-up using the ASSIST interface and the manipulator.



Integration on the ISS / Columbus external commercial platform Bartolomeo from Airbus



Configuration 1 for Satellite Assembly *Configuration 2 for Refueling & Coupling*

Figure 2. PERIOD system concept with the accommodation of the Factory on Bartolomeo.

The 2 robotic manipulators in the Factory Box are operated in the Satellite Kit Box (left hand-side box in Configuration 1) to pick up the different parts to be assembled. After the successful assembly demonstration, the empty Satellite Kit Box will be replaced by the Refueling Box (for configuration 2).

5. Robotic technologies

In the frame of the PERASPERA Strategic Research Cluster (SRC) [2], key enabling products have been selected for technology maturation aiming at an increased technology readiness level (TRL). In support of the PERIOD activities, ESROCOS, ERGO, InFuse and I3DS are developed to TRL5 after an alignment of their perimeter to the demonstration objectives. The Standard Interconnects (SI), already at TRL5 at project start, will be tested in a benchmark for evaluating their performance. These SRC building blocks will finally be integrated in a breadboard together with existing technologies from Airbus Defence and Space for supporting integration tests and system definition work.

5.1. ESROCOS

ESROCOS is a European Space RObot Control Operating System (RCOS) for space robotics applications. It provides an open-source 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 [3], [4]. The framework is based on the ESA's 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 [5], [6]. 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.

5.2. ERGO

The European Robotic Goal-Oriented autonomous framework [7], [8] is aimed to provide a set of software components and tools for the development of autonomous space applications in general and robotics in particular. It allows managing up to four autonomy levels. From E1 (direct telecommanding) to E2 (time-tag telecommanding), E3 (event-driven or uplinked plans) up to E4 (high-level goal commanding), which facilitate the handling of the autonomy level required for each specific mission and execution environment. ERGO implements a rigorous model-based development approach based on the ESROCOS framework and TASTE toolchain making the ERGO design approach generic enough to be applicable to any space robotics system (e.g. orbital robots, deep space probes, planetary rovers) as well as future terrestrial robots demanding a high level of autonomy. As part of the ERGO project, the framework was tested in two different scenarios: an orbital scenario simulating an in-orbit servicing mission, and a planetary scenario, inspired by the Mars Sample Return mission. Later, the framework was also reused, tailored, customised, and extended to the needs of other SRC projects related to in-orbit servicing scenarios (MOSAR [9], [10] and EROSS [11]) and planetary scenarios (ADE [12], [13], PRO-ACT [14]).

5.3. InFuse

InFuse is a building block developed in the SRC with the aim to offer a collection of computer vision and data fusion algorithms targeting space robotic applications (in space and planetary). The InFuse framework was further extended and adapted in a series of projects involving navigation capabilities of robotic platforms [15]. In EROSS, InFuse was tailored to address navigation in the rendezvous phase of a servicer with a client spacecraft, as well as tracking of its pose for the robotic manipulation. The methods used for the tracking were the model-based tracking (see Figure 3) as well as fiducial based tracking. Preliminary porting of these algorithms to the Zynq Ultrascale (ARM) architecture was successful. These results have high relevance to PERIOD, where previous algorithms will be further enhanced and adapted to the specific needs of the project in preparation for the follow-up phases. InFuse will be combined tightly with I3DS (detailed hereafter), to obtain high performances in the whole data acquisition and processing pipeline. Key primitives of InFuse will be wrapped into and run as part of the ESROCOS framework.

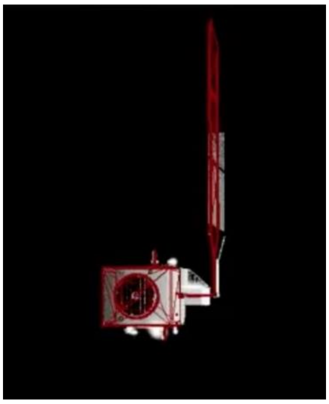


Figure 3: Model based satellite detection using InFuse.

5.4. I3DS

I3DS building block deals with a multipurpose suite of sensors selected and developed to address space robotics needs (both for orbital and planetary scenarios), along with the avionics required to handle data acquisition through these sensors. This includes visual and infrared cameras, a pattern projector, a time-of-flight camera, a start tracker, etc [16]. I3DS was used in all the operational grants of the 2nd wave of SRC projects, and will also be exploited in PERIOD, in close combination with InFuse. In PERIOD, though not consolidated yet, the sensors baseline will rely in part on the I3DS sensor suit (e.g. a Basler camera) and will be extended with additional sensors addressing specific needs, e.g. ability to perform high accuracy photogrammetry.

6. Standard Interconnect benchmarking

Standard interconnects (SIs) are becoming increasingly important in modular space robotics applications. With their use, it will be possible to connect different modular subcomponents in such a way that different configurations are possible. In the context of the mission scenarios of PERIOD, it means that, for example, different CubeSat configurations are equipped with one or more SIs and these CubeSats are interconnected in such a way that a functional satellite can be assembled. Currently, there is no recommended SI for the use in modular robotics in space. Therefore, an SI benchmarking is envisioned to be performed in the PERIOD project to give a recommendation on the SI to be used in the future phases of the project. Three SIs will be subject to the evaluation: HOTDOCK (from Space Applications Services), iSSI (from iBOSS GmbH) and SIROM (from SENER). The selection of an appropriate SI is crucial not only for the assembly and operations but also for the design of critical equipment like the manipulator with an impact to their development effort and costing. For the definition of the baseline of the SI benchmarking the ECSS-E-HB-11A handbook [17] and related standards are used as guidelines. Additional requirements to be considered by the benchmarking will come from the mission scenario of the PERIOD project [18].

7. PERIOD mission impacts

The PERIOD demonstration, as introduced in this paper, is believed to be ambitious and addressing new areas like satellite manufacturing when compared to other in-orbit demonstrations in preparation. This ambition is expected to produce major effects and footprints w.r.t. scientific, technological, societal and economic aspects.

In the short term PERIOD may produce following impacts:

- Generate new market opportunities to strengthen competitiveness and growth of European companies.
- Improve customer awareness on OSAM and its benefits.
- Inform transparently customers on capabilities, risks and mitigations.
- Demonstrate the feasibility of repeated IOD demonstrations for the OSAM use cases.
- Increase maturity of space robotics technology, servicing standard I/F and operations.
- Advance on standardization and regulations.
- Express proper needs w.r.t. OSAM including high variability in use cases considered.
- Demonstrate the feasibility to manufacture and assemble small satellites with larger antenna in space based on the integration of the SRC building blocks in a Factory.

8. Conclusion

One expected change in the paradigm shift engaged by the availability of game-changing technologies is the transformation of the lifecycle of space systems with a move of the AIT/AIV activities from Earth to the orbit, where space assets will be finally integrated and verified while in orbit. This transformation of the lifecycle will lead to new propositions like higher value of the systems, higher resilience, higher capacities and lower capital expenditure to provide improved commercial capacities. These new desired states can be reached with the development and deployment of servicing, assembly and manufacturing capabilities. Specific capabilities for Payload upgrade, Assembly of antenna reflector and Refuelling were selected as core demonstration elements based on the market analysis to be aligned on the stakeholder expectations. These capabilities will be phased according to the identified technology demonstrations and associated roadmaps. Due to the disruptive nature of the ISMA capabilities high impacts w.r.t. scientific, technological, societal and economic aspects can be expected.

9. Acknowledgements

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