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Outcomes of the PERIOD project on In-Space Manufacturing, Assembly and Refuelling Technologies

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Abstract. Traditionally, satellites and other space-specific assemblies (e.g., antennas, spacecraft, etc.) are built on Earth and then sent into orbit. New approaches are pursuing direct on-orbit manufacturing and assembly using robotics, autonomy, and modularity. The advantages are many, ranging from virtually unlimited overall volume and design of large satellite antennas to numerous options for building larger space infrastructures such as large reflectors and modular space stations. In addition, in-space manufacturing and assembly (ISMA) technologies can enable the upgrade and repair of existing spacecraft and satellites already in orbit, promoting the sustainable use of space through plug-and-play modularity. The PERIOD project is pursuing a concept in which an orbital demonstrator is being developed for satellite manufacturing and assembly, as well as docking and refuelling experiments. This paper describes the background of the development, the PERASPERA building block technologies ESROCOS (European Space Robotics Control and Operating System), ERGO (European Robotic Goal-Oriented Autonomous Controller) and InFuse (Data Fusion) used, the test setup of the demonstrator and first results. The successful implementation and validation of ISMA technologies will lead to the generation of independent European capacities allowing Europe to build future orbital infrastructure and to be competitive on the ISMA markets

1. Introduction

The consequence of decades of orbital activities is a lot of space debris. Numerous projects are addressing how to sustainably continue space activities in the future. One of many approaches is the concept on In-Space Manufacturing, Assembly (ISMA). This involves building large assemblies in the current orbital environment, rather than on Earth. This includes the construction of satellites in orbit as well as the maintenance and repair of existing objects, if possible. With the help of robotics, modular components can be connected with each other in orbit so that, depending on the application, correspondingly adapted assemblies (e.g. satellites, antennas, etc.) can be created. Concepts of robotic spacecraft maintenance and assembly date back to the early 1980s [1]. Successful examples are the Shuttle Remote Manipulator System, or Canadarm, the manipulator systems of the International Space Station (such as the Space Station Remote Manipulator System and the Special Purpose Dexterous Manipulator) as well as the Engineering Test Satellite VII "KIKU-7" and Orbital Express missions [2]. However, despite these successes, unmanned and completely autonomous missions have yet to become operational [3].

New approaches include the use of autonomously acting robotic systems that independently combine modular components. This is where the PERIOD project comes into play. The PERIOD (PERASPERA In-Orbit Demonstration) project has the goal to demonstrate on the ISS key robotic technologies to enable ISMA and On-Orbit Servicing (OOS) applications. This includes in-orbit manufacturing of a modular spacecraft equipped with an antenna that is to be assembled in-orbit as well [4]. In the course of the project, existing multifunctional interfaces in Europe were tested for their usability in relation to the planned demonstration scenario in a benchmark [5]. The so-called Standard Interconnects (SIs) HOTDOCK [6] and SIROM [7] are used in the PERIOD breadboard demonstration. The demonstration scenario further builds on modular components such as CubeSats, which, equipped with multifunctional interconnects, can be combined with each other using a manipulator arm to create functioning assemblies [8].

The autonomy underlying the processes comes from predecessor projects ESROCOS (European Space Robotics Control and Operating System) [9], ERGO (European Robotic Goal-Oriented Autonomous Controller) [10] and InFuse (Data Fusion) [11].

The PERIOD demonstration scenario is intended to underline the envisaged ambitious IOD to lead to the manufacturing of a functioning satellite in an 'orbital factory' accommodated on the ISS Bartolomeo platform 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.

The paper describes the setup of the demonstration scenario, first test, results and conclusions and outlook.

2. Demonstration Setup

In this section the setup of the integrated breadboard demonstration is described. Especially the modifications of the RISMAT testbed are documented and the version of the testbed is explained in detail that forms the main facility for all tests and demonstrations of the PERIOD phase B1.

2.1. Airbus DS RISMAT Test-Facility

Within the MANTOS Project [12], a test facility was set up that makes it possible to verify robotic operations in a closed functional chain. For this purpose, the physical components such as manipulator, tools, the ground station as well as the software/skills for performing the robotic operations had to be implemented in an integrated test setup. The functionality of the components and the feasibility of selected robotic operations was tested with respect to the performance of individual functions as well as the interaction of different components. The verification of the robotic operations with respect to collision avoidance and the path planning take place in a Virtual Reality (VR) environment before installation and execution in the testbed.

The servicing part is modelled on the experiment stations of the Bartolomeo platform. The dimensions of the tool magazine (satellite assembly box) and the satellite servicing rack (robotic factory box) correspond to those of the experiment stations on the Bartolomeo platform of AIRBUS Defence and Space. The setup thus also serves to prepare for follow-up projects in the environment of the Bartolomeo platform. For the robotic operations, a KUKA/R14 is used, which is part of the infrastructure of the robotics laboratory at Airbus Defence and Space in Bremen. In its kinematics (length, joint configuration) the manipulator does not correspond to the manipulator used in orbit. It is suitable for testing the MANTOS objectives, because it can move the Multi-Purpose Tool (MPT) with the sockets even under 1g conditions.

2.2. Modification of RISMAT-Testbed for the breadboard Demonstration

The update of the RISMAT testbed for the integrated breadboard demonstration in PERIOD is shown in the following drawings.

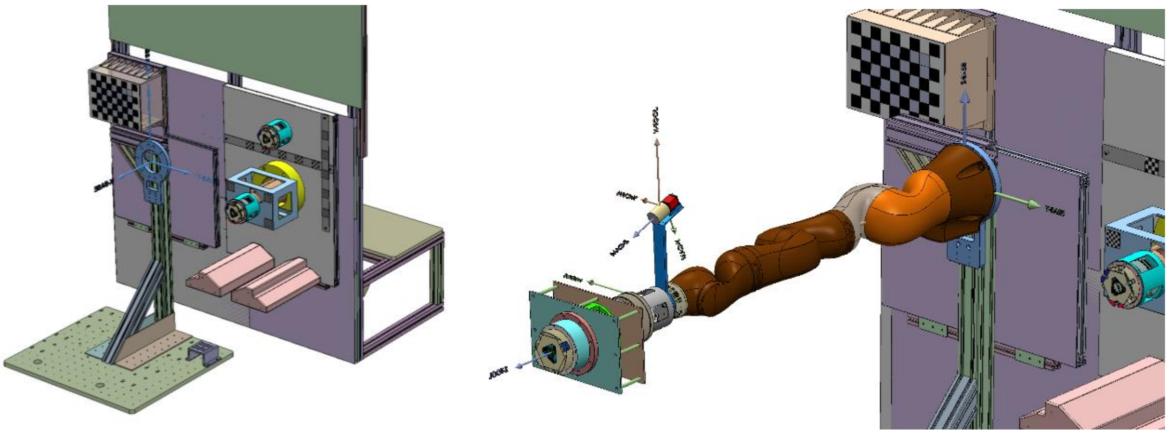

Figure 1 RISMAT design for the PERIOD integrated breadboard demonstration

Two Bartolomeo boxes are foreseen to carry some of the relevant PERIOD structures. The left box is a substitute for the work bench and the tools and the RCU (Robot Control Unit). Here only the RCU is represented with a calibration pattern (chessboard pattern) attached to it. On the right side a storage for the payload on top of a SIROM interface is foreseen. This SIROM is attached to the backplane of the updated RISMAT testbed.

Below this storage, a mock-up of the Kaber deployer and the satellite kit-box is foreseen. As the satellite and the Kaber deployer have no functions here they were mimicked just as passive elements that provide an interface to another SIROM SI attached to the satellite. Both SIs are supplied with power and CAN bus via specific harness that is connected with the central RCU.

The payload itself consists of a box equipped with two passive SIs. One passive HOTDOCK for connecting to the end-effector and one passive SIROM for connecting to the payload storage and the satellite kit-box.

Finally, the end-effector of the KUKA robot is equipped with a HOTDOCK SI in order to connect to the payload. Furthermore, a camera mount is designed to carry the end-effector camera and to allow the camera to see the markers and the background even when grasping the payload.

In the end the KUKA iiwa R14 robot is attached to the updated RISMAT testbed. It is attached to a structure that can be moved on a linear rail. For the purpose of the PERIOD demonstration the rail is not used, and the KUKA remains stationary. It is moved approximately by 0.5 m in order to provide better reachability to the grasping points in front of the payload storage and the satellite kit-box.

The camera that has been selected is a MAKO camera by Allied Vision. It is equipped with the CMV4000 detector by CMOSIS that has been selected for many different space cameras. The lens was chosen to be a RICOH lens with a field of view of approximately 70°.

The next figure shows the setup of the updated RISMAT after modifications.

Figure 2 RISMAT after modification for the purpose of the PERIOD integrated breadboard demonstration.

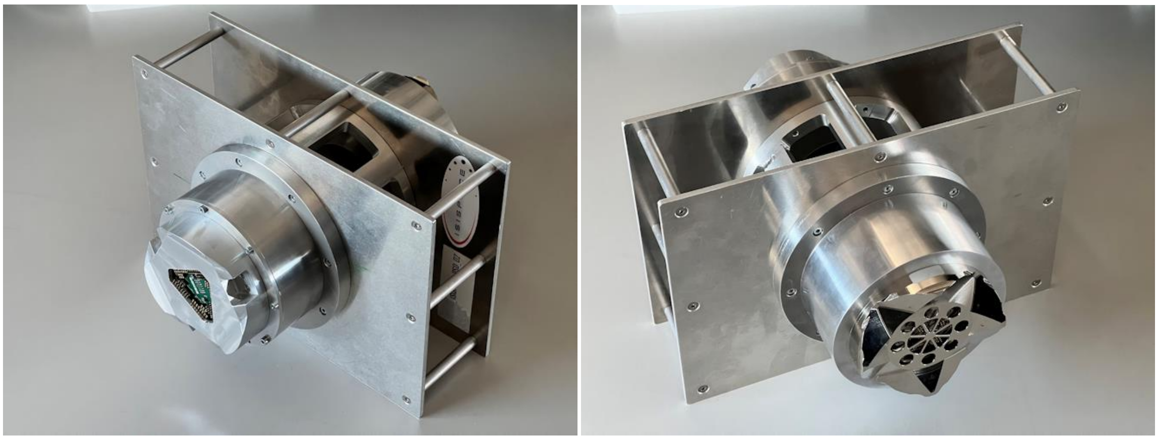

Figure 3 Payload element equipped with two SIs: SIROM (left) and HOTDOCK (right).

The on-board computer is based on a modular ruggedized PC104 Intel Atom based computer which has been selected also as a flight computer (e.Cube). In order to estimate capabilities of this computer, a relevant Software Development Model has been selected for the demonstration. The simulation and ground control station is based on a standard x86 PC with powerful NVIDIA graphics card. The Robot Control Station (RCS) is also based on the Intel Atom architecture but uses a less ruggedized version.

2.3. Modifications of the software architecture

The PERIOD software (S/W) architecture (Figure 4), defined for the ground and flight models to perform the in-orbit demonstration (PERIOD phases D/E), has been also customised and tailored (Figure 5) to the needs of the PERIOD breadboard demonstration to be integrated in the RISMAT testbed (PERIOD phase B1).

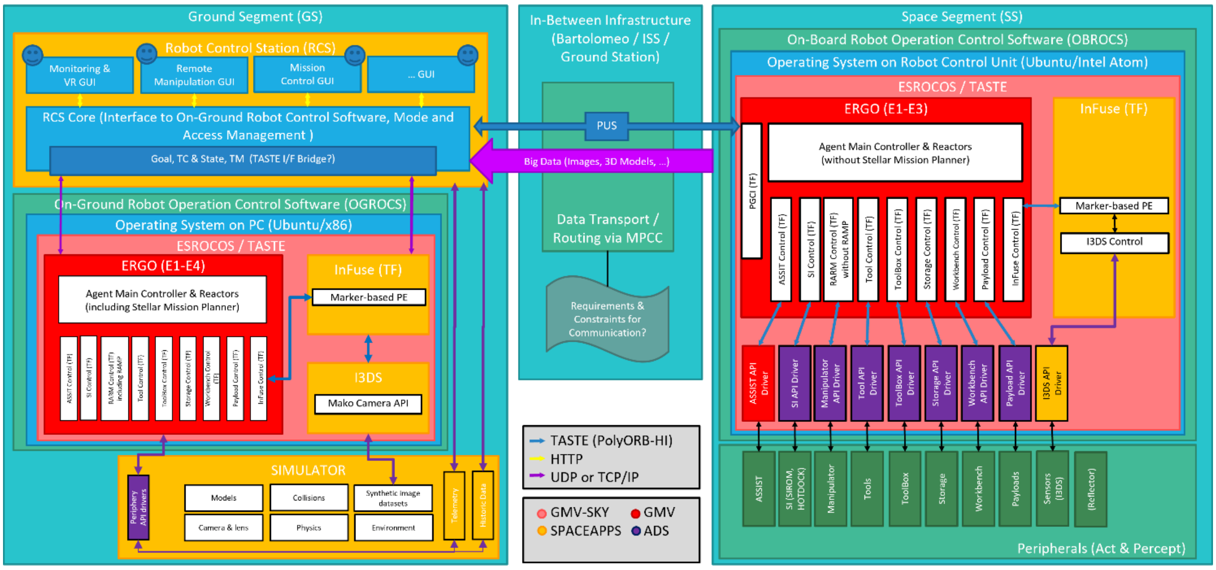

Figure 4 PERIOD S/W architecture for in orbit demonstration (PERIOD phases D/E)

The control software provides for a decentralized approach, with a share between the ground and flight segment. Critical components necessary for reactive real-time control of the robotic factory are to be executed on-board, while the deliberative, non-time-critical, computationally and memory intensive components run on the ground, since their results must be verified by means of simulation and human operators before execution anyway.

Figure 5 describes the result of the customisation and tailoring of the PERIOD S/W architecture to the breadboard implemented in the RISMAT testbed environment used in PERIOD for the proof-of-concept demonstration.

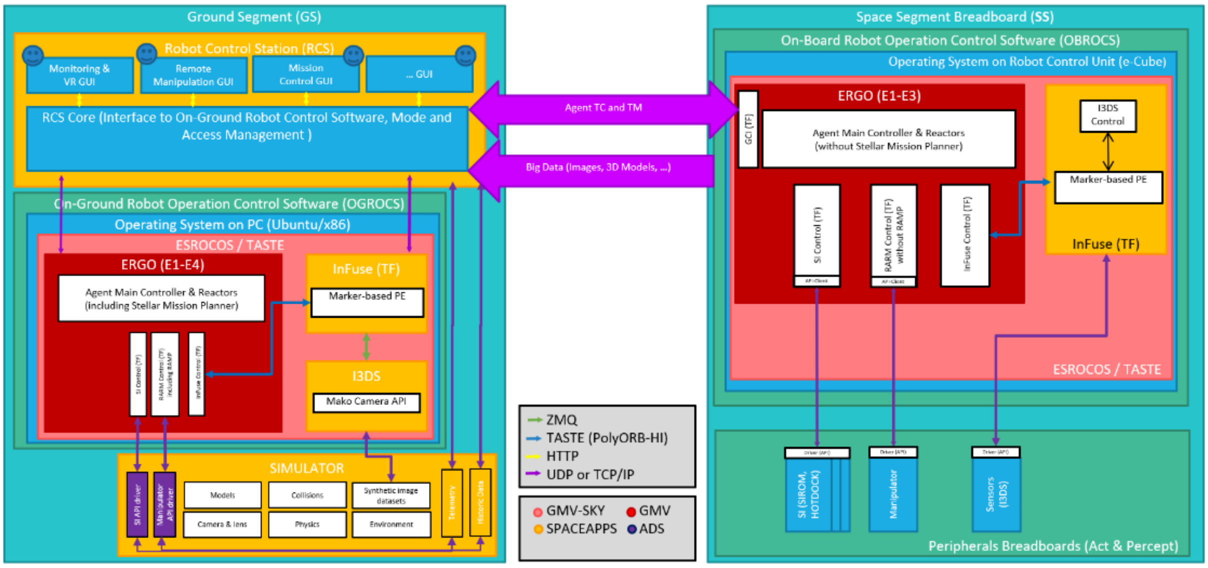

Figure 5 RISMAT S/W architecture of the testbed demonstrator (PERIOD phase B1)

This S/W architecture customisation and tailoring concerns especially the fact that not all peripherals of the final PERIOD stage have been developed and fully integrated. Only the necessary components for the realization of defined relevant use-cases were developed and integrated.

Furthermore, the RISMAT testbed communication channel between ground and flight segments does not include the “In-Between Infrastructure (Bartolomeo/ISS/Ground Station)” so the PUS interface does not apply. Instead, a dedicated communication channel (based on TCP/IP) has been established.
The PERIOD S/W testbed architecture (Figure 5), deployed in the RISMAT demonstrator, still respects a clear definition of the Ground and Flight Segments, but customised and simplified for the testbed current environment.

3. Demonstration Execution and Results

At the end of the phase B1 of the PERIOD project, all critical S/W components were tested in an integrated breadboard demonstration according to a previously defined test plan. The test plan foresaw nine different operational test-cases ranging from on-board calibration to replacement of payloads on board of the mock-up of the Bartolomeo boxes.
This breadboard demonstration was presented during the SRR of the project in front of representatives of the EC and the PSA. Figure 6 and Figure 7 show snapshots of the live-demonstration. Figure 6 (left) shows the robot with the robot-end-effector-SI just connected to the SI of the silver payload element. Figure 6 (right) shows a view of the end-effector camera and with an overlay of the resulting pose-estimation which was applied to correct the end-effector position. Figure 7 shows further steps of the performed mission sequence including the connection to the payload module (left), the release of the payload module (centre) and the release of the payload module after attaching it to the satellite-mock-up (in black) (right).

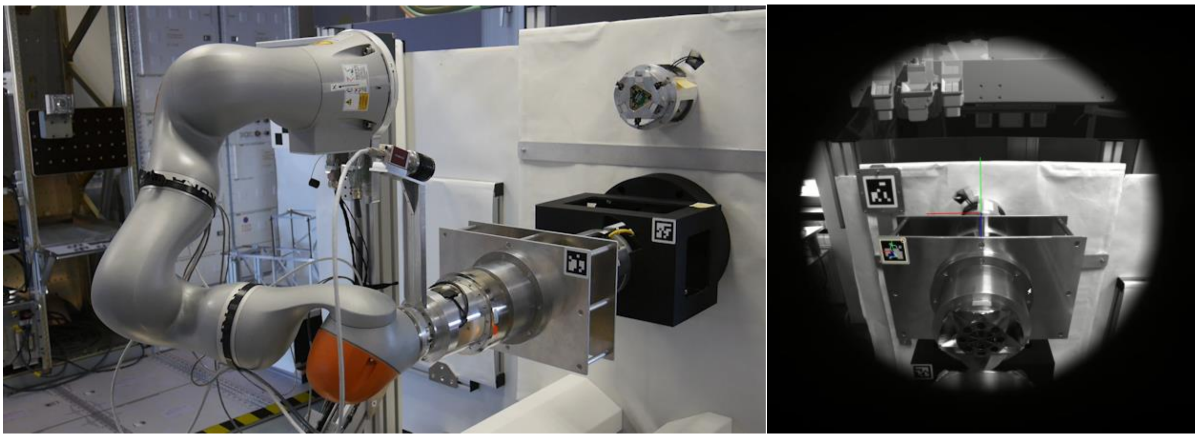

Figure 6 View of the robot during the exchange of the payloads (left) and visualization of the camera image captured during the process of automatic pose-estimation of the payload for accurate positioning of the manipulator.

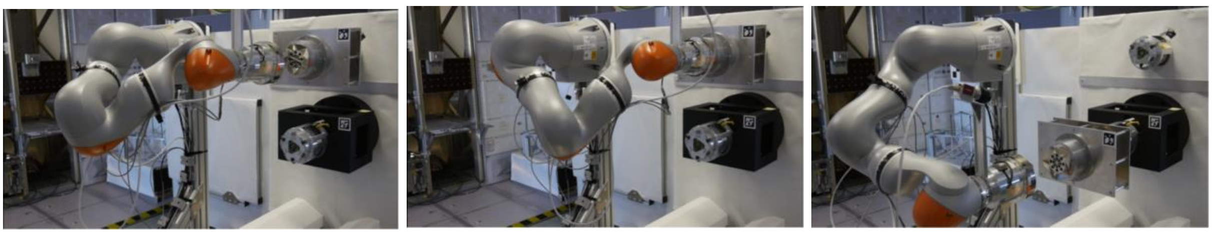

Figure 7 Tested mission sequence: Exchange of a payload equipped with two different standard interconnects. All available PERASPERA building blocks were integrated and demonstrated in this test-scenario: ESROCOS, ERGO, InFuse, i3DS and the two SIs SIROM and HOTDOCK. All elements were integrated in the AIRBUS RISMAT testbed.

The full demonstration was performed by using the integrated demonstration breadboard, but more important based on the full stack of S/W elements described in section 2 including ESROCOS, ERGO and InFuse building blocks.

4. Conclusion and Outlook

In the breadboard demonstration integrated in the RISMAT testbed, the objective was to demonstrate and validate the capability and effectiveness of robotic building blocks together with hardware peripherals and/or mock-ups that have been developed in the frame of the project PERIOD. An additional objective was to get a relevant testbed environment to reach and validate TRL5 for the critical software components. Here the focus was on the demonstration of how the different building blocks and peripherals/mock-ups can operate together in order to solve a relevant assembly task (system proof-of-concept).

The previous test mission was completely developed and integrated with the prepared on-board software (including the PERASPERA software building blocks ESROCOS, ERGO, InFuse and I3DS). Missions were pre-planned and executed with the developed on-board software.

The integrated hardware included the PERASPERA SI building block SIROM SI and HOTDOCK SI. As a sensor a commercial camera has been applied for which a dedicated driver has been integrated into I3DS. The robot itself was an industrial KUKA iiwa robot for which a dedicated driver in ESROCOS and motion control stack in ERGO have been integrated.

With all these elements a complex and representative satellite assembly scenario could be executed that included all previously planned test-elements according to the test-plan and the test requirements on breadboard demonstration level. Also the software of the ground system could be demonstrated. The RCS coupled with the ERGO mission planner could generate the mission timelines based on an on-ground-representation of the flight system. These missions could be evaluated in simulation and then prepared for execution on the on-board system. Some telemetry data could be observed during mission execution but here especially some points are still missing which should be implemented and tested in future project phases.

In the following only some points for the future should be addressed:

- Communication between ground and flight system were performed on dedicated communication channels. No space protocols like CCSDS or PUS were used yet, although the PUS are already available in the frame of ESROCOS.
- Ground commanding and monitoring from ground is prepared and the required S/W libraries and tools have been prepared. The RCS is ongoing work and provides all capabilities to setup a future robotic control station.
- Not all telemetry data was currently provided that is available in principle from the flight elements. A dedicated analysis of all needed TM data is required and has to be implemented later on.
- Motion planning is based on stochastic optimization and provided several trajectories for the same conditions. It is based on the open source S/W OMPL, developed by PikNick robotics who also implements the MoveIt package of ROS. The non-deterministic outcome of the motion planning was observed.
- It is not clear to which extent this open source S/W is fully space-qualifiable. As long as this is only part of the ground S/W, this however should not be a problem.
- Hand-eye-calibration was performed in a dedicated off-line process and is currently not integrated into any of the frameworks. This should be done in later development stages in order to be prepared for a necessary on-board calibration of the robot and its camera system.
- The image processing is currently based on open-source S/W Open CV and makes usage of the ARUCO library. It is not clear how this open source S/W can be space-qualified. This is needed because it is currently foreseen to be part of the on-board S/W. An alternative could perform computations on ground.
- Currently there is no check of integration of pose-estimation results in terms of re-planning of the trajectory. This should be checked if it is necessary.

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