MOSAR: Modular Spacecraft Assembly and Reconfiguration Demonstrator

Pierre Letier[1], Xiu T. Yan[2], Mathieu Deremetz[1], Alessandro Bianco[2], Gerhard Grunwald[3], Maximo Roa[3], Rainer Krenn[3], Miguel Muñoz Arancón[4], Pierre Dissaux[5], Juan Sánchez García Casarrubios[6], Rodrigo Ruiz Lucini[6], Luca De Filippis[7], Giuseppe Porcelluzzi[7], Mark Post[2], Michael Walshe[8], Philip Perryman[8]

[1] Space Applications Services SA, 325 Leuvensesteenweg, 1932 Sint-Pieters-Wolluwe, Belgium, pierre.letier@spaceapplications.com

[2] University of Strathclyde, Design, Manufacturing and Engineering Management, James Weir Building, 75 Montrose Street, G1 1XJ, United Kingdom, x.yan@strath.ac.uk

[3] German Aerospace Center (DLR), Institute of Robotics and Mechatronics / Institute of System Dynamics and Control, 20 Münchener Str., 82234 Wessling, German, Gerhard.Grunwald@dlr.de / rainer.krenn@dlr.de

[4] GMV Aerospace and Defence, Isaac Newton 11 PTM, Tres Cantos, 28760 Madrid, Spain, mmunoz@gmv.com

[5] Ellidiss technologies, 24 Quai de la douane, 29200, Brest, France, pierre.dissaux@ellidiss.com

[6] Mag Soar S.L, Avenida de Europa 82, 28341,Valdemoro, Spain, jsanchez@magsoar.com

[7] SITAEL S.p.A., Via San Sabino, 21, 70042 Mola di Bari (Italy), luca.defilippis@sitael.com

[8] Thales Alenia Space UK LTD, 2 Dashwood Lang Road, KT15 2NX Weybridge, United Kingdom, michael.walshe@thalesaleniaspace.com

ABSTRACT

With rapid development of space systems in recent years and their limited lives, it is imperative that a sustainable space development approach is developed to support more affordable access to space for all stakeholders. The European Commission hence funded the MOSAR project which aims to create a new paradigm technology to address this increasing challenge. This paper provides an overview of this technology's preliminary development to enable on-orbit servicing. Building on five successful projects which collectively created all required common building blocks for both planetary explorations and in-orbit missions, a novel architecture is proposed to create a walking manipulator to demonstrate its unique capability in both space system assembly and on-orbit servicing. Preliminary design concepts of a walking manipulator and spacecraft modules are shown. A dedicated simulator is also developed to evaluate the proposed novel architecture for these targeted applications.

1. INTRODUCTION

Offering cost effective, high performing, reliable, scalable and flexible solutions will be essential for the European space industry to spearhead strategic segments of the commercial space industry. To reach this goal, the European Commission has established the Strategic Research Cluster (SRC) in Space Robotics Technologies within the H2020 program. Through three successive calls, it aims at developing and demonstrating robotic key technologies for orbital and planetary applications. After the first call initiated in 2016, targeting the development of robotic common building blocks, the purpose of the second call is to develop ground demonstrator of advanced robotics for both orbital and planetary illustrative scenarios.

As a funded project of the second call, the Operational Grant (OG) 9 - MOSAR project, started in March 2019, aims at developing a sound technology demonstrator for on-orbit modular and reconfigurable satellites. The project targets to integrate and demonstrate technologies required to enable a fundamental shift of paradigm in designing and deploying satellites in future. The new approach will cater to the whole end-to-end life cycle of satellites from their inception to their commissioning, and even more importantly covering their maintenance in a completely new business model. Potentially, the proposed approach is equally applicable more widely for in-space construction of many spacecraft and their maintenance.

The MOSAR initiative aims to raise the degree of modularity of targeted space systems by an order of magnitude with respect to current space industry standards. It would represent the beginning of a new era in space missions, in which the entire spacecraft could be optimized to fulfill mission requirements in a much more efficient and dynamic way.

2. MODULAR DESIGN APPROACH FOR SPACECRAFT

Existing commercial satellites and space platforms are traditionally the result of a highly customized monolithic design with very limited or no capability of servicing and maintenance. This approach has been followed in the past due to main constraints of mass and launch costs optimizations. From this heritage, the number of aging satellites is growing rapidly. There is no available technology hence typically no plan for maintenance and the aged satellites are simply dismissed and left in orbit as a space debris. Beside the evident space sustainability issues, this also creates constraints on space economy actors. Their missions, supply chain organization and commercial planning need to be carefully planned in advance. On the other side, there is currently an overall trend to decrease launch costs (per kg) while increasing launch capacity and opportunities. Taking into account the faster industry evolution and the need for more flexibility, there is a growing interest in new technologies and methodologies for space vehicles design and operation, which includes system modularity.

In a modular design, the satellite is composed of several compatible independent modules. Each module presents an abstraction at the functional level, having a specific purpose in the global structure. Interconnectivity regarding the compatibly is ensured by standardization of the module design and its interface.

Standardized manufacturing of spacecraft components enables a higher degree of flexibility and better reusability while reducing lead-time from a customer's orders to commissioning in space. It moreover allows moreover optimization of the manufacturing, integration and qualification process for significant cost reduction with possible economy of scale. Through modularization, a better reconfiguration for more functionality and better flexibility could increase market segmentation and open opportunities to new manufacturers and suppliers.

These modular and reconfigurable robotic technologies therefore potentially create opportunities for a systematic approach to On-Orbit-Assembly (OOA) and On-Orbit Servicing (OOS), for a radical change of spacecraft construction and operations. It could make it possible to perform maintenance, repair and upgrade components directly in space, and extend satellite lifetimes instead of getting rid of them (de-orbiting) when deprecated or damaged. This will have a direct impact on total mission costs, reliability and sustainability. Through reconfiguration and upgrades, satellite owners will be able to re-plan satellite functions with agility, responding to new commercial requirements. A new responsive supply chain model will be established and it will lead to an increase of the development pace of space application technologies and to a blooming of new services and product in the space industry.

The concept of space modularity has been already explored in the past either through the development of re-usable modular space subsystems or through concepts of assemblies of generic modular components [3]. The innovative approach of the MOSAR project is to elaborate and refine the concept of modular spacecraft, bringing together different actors of the space industry including satellite manufacturers and companies involved in modular space design, while relying on the re-use of hardware and software generic common building blocks developed during the first call of the SRC activities. These components have been created to be the standard elements of future European space projects, and in the current context of the space industry described above, this can create the conditions to leverage the paradigm shift towards modular space systems. The project aims at creating a demonstrator by recommending and deploying standard building blocks, and proposing progressive deployment and strategy for economical exploitation in the space industry. This will be mainly done through the implementation of a ground demonstrator of on-orbit modular satellite reconfiguration relying on robotic capabilities and simulation, as presented in the following sections.

3. MOSAR DEMONSTRATOR

3.1. MOSAR Scenarios and Architecture

The notional scenario of the MOSAR project is illustrated in Figure 1. A Servicer Spacecraft (SVC) transporting a cargo of Spacecraft Modules (SM) and a dedicated Walking Manipulator (WM), performs a rendez-vous and docking with a Target Spacecraft (TGT) bus and then realize a number of operations with the transfer of modules from and to the TGT.

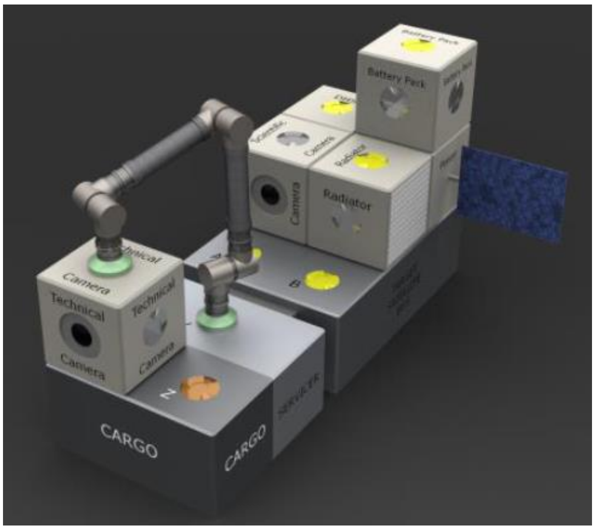

Figure 1. MOSAR demonstrator setup

More specifically, the following application scenarios will be demonstrated under laboratory conditions:

- Initial transfer of spacecraft modules from the Cargo to the Target satellite, including 3-point connection (cube corner);
- Replacement of a damaged module on the Target, with hot-reconfiguration procedure and re-routing of the power/data bus;
- Thermal transfer to demonstrate the active cooling of a Module producing heat with a dedicated thermal handling module.

To achieve these demonstrations, several components are under development including:

- A repositionable symmetric walking robotic manipulator allowing to capture, manipulate and position spacecraft modules, while being able to reposition itself on the spacecraft elements or directly on the modules;
- A set of spacecraft modules as part of a global eco-system highlighting different functional purposes, like control, power, data or thermal sub-systems or active payload modules as optical or Time of Flight sensors;
- A functional engineering simulation environment offering assistance for modules design, system configuration and planning, through multi-physics engine;
- A testbed setup representing the servicer and target satellite including a Monitoring and Control Centre to support validation activities and integration of the engineering simulator.

These components will be described in the following sections, including the integration and re-use of the common building blocks developed in the 1st call of SRC activities.

3.2. Common Building Blocks

The reuse of the Common building blocks (CBBs) developed in the 1st call of the SRC activities is a requirement of the MOSAR project and more importantly gives a headstart. By building on the work performed in the first call, MOSAR will benefit from the past investment and the possible synergies with the parallel SRC activities in order to attain its objectives in a cost-effective manner. Conversely, the usage of the CBBs in MOSAR will contribute to their maturity and their adaptation to the demands of new applications.

The first building block is ESROCOS (European Space Robotics Control and Operating System) [2], a model-based framework for the development of space robotics applications. It will be used to model the system components and their interfaces. ESROCOS currently supports only static systems, and will have to be extended to provide support for reconfigurable systems, in order to fulfil the needs of the satellite reconfiguration scenario.

The second one is ERGO (European Robotic Goal-Oriented Autonomous Controller) [3]. ERGO is a framework for the development of autonomous capabilities in robotics applications, addressing the four autonomy levels E1 to E4 described by the ECSS Space Segment Operability standard [4]. The core of the framework includes a generic robotic controller or “agent” that can be embedded into functional blocks using a common interface to compose n-layered control architecture of reactive and deliberative components. The agent is integrated with the Stellar planner, a generic mission planner that supports temporal Planning Domain Definition Language (PDDL) [5] models. ERGO will be deployed on the simulation environment for planning and validation of the satellite reconfiguration plan, and on the on-board system for plan execution. PDDL models of the reconfiguration problem and the domain will be developed. Additionally, ERGO components for robotic arm path planning will be assessed for reuse.

The third CBB is InFuse, a Common Data Fusion Framework (CDFF) for implementation and integration of data fusion algorithms [6]. InFuse allows the definition of DFNs (Data Fusion Nodes) as basic re-usable building blocks, and the definition of DFPCs (Data Fusion Processing Compounds) as any complex computation composed of DFNs. In its current state, InFuse includes several 2D and 3D image processing DFNs, and some extended DFPCs such a 3D Reconstruction pipeline. In addition, InFuse includes a type library in ASN.1 format, a code generator that allows the conversion of YAML specification into a C++ stub for ease of implementation, and a set of DFN testing tools. The three dimensional reconstruction capability within InFuse will enable the creation of a 3-D model of a target spacecraft module so that the precise location and the interfacing features can be modelled and measured to guide the planning of autonomous manipulation in assembly or servicing.

The fourth building block is I3DS (Integrated 3D Sensors). I3DS comprises of an ICU (Instrument Control Unit) and a suite of sensors to assist autonomous navigation in space robotics missions. This includes cameras (stereo, TIR, Hi-Res), LIDAR, RADAR, Force/Torque sensors and a Star Tracker. The ICU interfaces with the sensor suite and provides data products to the OBC/EGSE over a single link using ASN.1 packetisation. The ICU software is built on a custom framework designed during the I3DS project, which allows the consumer of I3DS data products to subscribe to service nodes for the sensor(s) of interest. The ICU itself is based on the Xilinx Zynq UltraScale+. In MOSAR, the design of the ICU will be the extended to address the avionics functionalities of the spacecraft modules. In parallel, some of the sensors and their related software will be implemented to enable the performance of the demonstration.

The fifth building block is the SIROM interface, which is a compact standardized and multi-functional interface with the capabilities of mechanical, power, data and thermal transfer between modules and spacecraft or payloads. The interface will be used to allow mechanical connection between the modules themselves and the spacecraft, as well as with the walking manipulator, which will be equipped at each of its extremities. Improvements of the interface are under investigation to address the specific requirements of the MOSAR project and demonstrations, including the load transfer, diagonal engagements, form-fit guidance and controller and power electronics integration. The interface will be the basis for the mechanical integration and integrity of a space system whilst transferring power and data between the components. In the context of the third scenario, the thermal interface, developed in the SIROM activity, will be updated. The Closed Loop Fluid Heat Exchange Module (CL-FHEM) shown in Figure 2 will be used as a baseline for the Thermal Subsystem. This system will be demonstrated through heat transfer between a heat source payload module and another one equipped with a dissipation radiator specifically developed for space environment conditions.

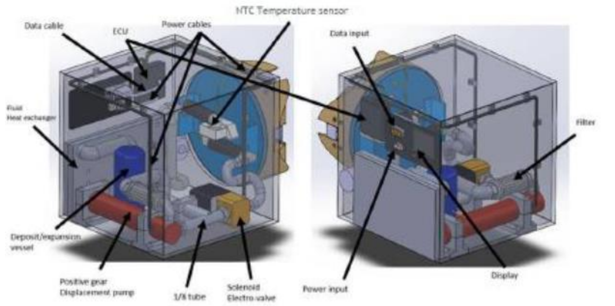

Figure 2. MOSAR CL-FHEM module

This technology opens a wide range of opportunities in the space sector, for human precursor missions and for orbital satellites, but also knowledge can be transferred to other engineering fields such as transportation or industrial activities such as deployable fluid exchange systems for cryogenic environments.

3.3. Walking Manipulator

The design of a robotic walking manipulator is one of the main challenges within MOSAR since its main feature relies on its ability to change its attachment point from one edge to the other edge to move around within the desired workspace, i.e., as a difference to a fixed base manipulator. As a key technology for the planned demonstration, the walking manipulator is designed to grasp, position and deposit payloads from the servicer's cargo area to the target satellite bus and vice versa. To this end, each extremity of the walking manipulator is equipped with a standard interface also called docking interface.

These unusual features of the manipulator have major consequences for the design. Indeed, the relocation ability implies that the structure of the robotic arm has to be similar whatever the attached extremity may be. This calls for a kinematic chain with at least 7 DoF, preferably with modular joints, and most likely with symmetric distribution of joint modules to facilitate both the displacement and manipulation actions, favoring high torque against motion speed. Motion accuracy is also a key characteristic to deal with that requires backlash minimization at the joint level. According to the selected scenario and its application into space, the walking manipulator has to be designed to minimize the overall footprint and the power

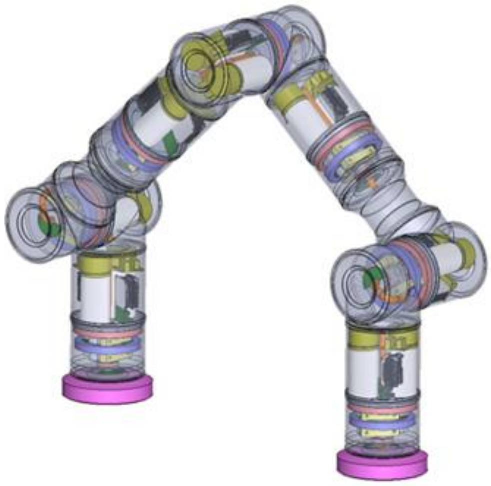

Figure 3. MOSAR Walking Manipulator Concept

consumption. Such a walking manipulator concept is depicted in Figure 3.

In term of control, the ambition linked to the robotic arm is to provide a position and torque mode (e.g. it can implement compliant control), thus providing the dexterity and accuracy required to precisely assemble/disassemble components of a reconfigurable spacecraft. Moreover, to allow high level control and power supply, the robotic arm should be equipped with a power grid and connected to the spacecraft communication network through the docking standard interfaces. The challenge will be to keep power and data communication running while robot moving along the structure.

3.4. Spacecraft Modules

Modularity is expressed on the satellite structure as the capability to build the platform through standard thermo-mechanical modules assembled and interconnected together through standard interfaces. As illustration of an eco-system and for the purpose of demonstration, a set of active sub-system modules and active payload modules will be designed in the project. They will cover the envisaged principal functionalities including a data management, power, battery ORU and thermal sub-systems, as well as optical sensor and time of flight payload modules.

A standard cubic shape for the modules has been selected in MOSAR with a baseline edge between 30 and 40 cm. The target implementation foresees the capability to integrate a standard interface on each face of the module (limited in this demonstrator to 3 per module). Figure 4 shows a preliminary sketch of the module structure with slots for the standard interface and customized payload or sub-system

The module external structure will be built with beams and panels in order to guarantee high standardization during design and interface definitions, manufacturing and integration. The mechanical structure will be optimized to guarantee a minimum weight of the structure (to reduce constraint on the manipulator design) while ensuring mechanical stiffness and resistance to cope with stresses exerted by the presence of or the manipulation through the walking manipulator. The module design will be designed such that it will facilitate multiple connections with it adjacent modules interfaced by the manipulator.

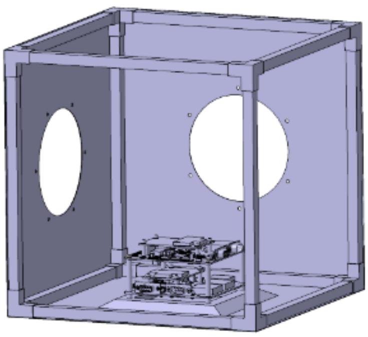

Figure 4. Preliminary concept of Spacecraft Module external and internal structure

In order to simulate in-orbit operational scenarios, two test benches will be designed, reproducing the servicer (SVC) and the target (TGT) spacecraft. The interface setup implemented in MOSAR to simulate the spacecraft assembly and reconfiguration procedures, will include 6 modules, 1 primary test bench (simulating the TGT platform) and 1 secondary test bench (simulating the SVC platform).

3.5. MOSAR Avionics and Architecture

The communication network topology imposed by the type of missions targeted in MOSAR is a “fully connected mesh network” topology (at least a full exploitation of paths redundancy between the Spacecraft Modules is desired).
In the CBB of OG5, two interfaces for communication were implemented: CAN and SpaceWire, as shown in Figure 5. The CAN bus is ideal for low bandwidth deterministic communications up to 1Mbps for TC/TM messages. SpaceWire provides the means to transfer large amount of data as produced by a payload sensor. These technologies complement each other also from a topological viewpoint, the CAN being mainly deployed on a bus network topology while the SpaceWire is applicable to point-to-point links or in mesh and star networks by means of SpaceWire routers. In MOSAR, since the CAN bus is not suitable for this network topology, a combination of local CAN bus and SpaceWire mesh/star network is deployed to route messages to a destination. The CAN technology is used as a local bus to control the components of a spacecraft module or the robotic manipulator and its associated standard interfaces. The SpaceWire technology is used for communicating between the Spacecraft Modules (APMs/ASMs) through a mesh of SpaceWire routers, and also present functionality to convert the CAN messages carried over the SpaceWire network to the CAN bus (CAN over SpaceWire).

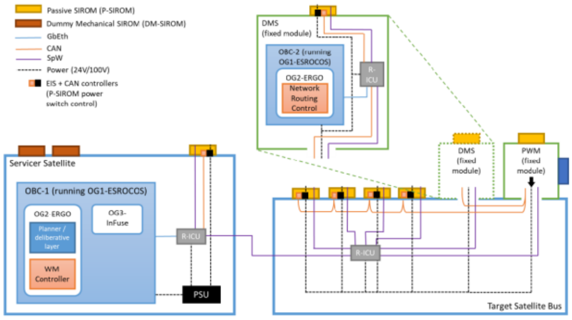

Figure 5. MOSAR Preliminary Architecture

3.6. Simulator

Many activities of the MOSAR scenario such as task planning, robot path planning and control, assembling and disassembling of modules, or attitude control of a spacecraft with a versatile topology have to be carefully prepared and verified. In order to support the overall system design and operational planning process, a functional engineering simulator (FES) is currently being built. The FES will include:

- models of the orbital environment,
- models of the spacecraft modules with their individual equipment like reaction wheels, thrusters, antennae or solar panels,
- a model of the controlled robotic arm operating on the spacecraft modules,
- the same control interface used by the hardware demonstrator

The models required to build up the FES are designed using Modelica. The Modelica standard library provides powerful tools to solve multi-body dynamics, electrical, and thermal modelling problems. Particular problems of the MOSAR reference scenario are covered by the DLR SpaceSystems library shown in Figure 6, the DLR RobotDynamic library and the DLR SimVis visualization library. The preferred engine for Modelica model editing and simulation within MOSAR is the commercial software product Dymola (Dassault Systemes).

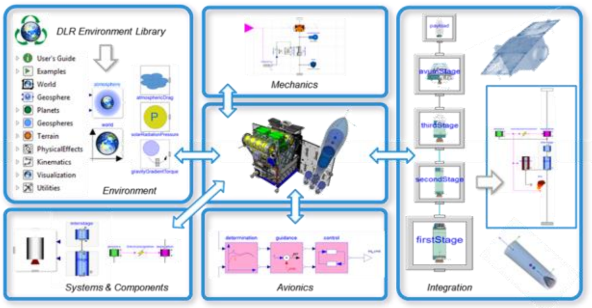

Figure 6. Components of the DLR SpaceSystems library

4. MOSAR DEMONSTRATOR WORKFLOW

Figure 7 illustrates the typical workflow of modular satellite reconfiguration, which is implemented through an iterative process of design, multi-physics verification (based on the simulator), operation planning (based on CBB ERGO), sequence verification, server plan updates, execution and monitoring (also through ERGO).

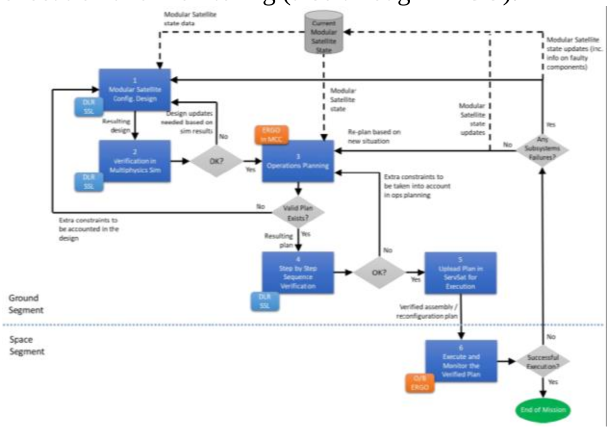

Figure 7. Modular Satellite design workflow

5. DISCUSSION, FUTURE WORK AND CONCLUSION

Within MOSAR, we expect to raise the global TRL level of the relevant technologies from a current state of TRL 3 to reach a global TRL level of 4 to 5.

The MOSAR project started in March 2019. The consortium is currently finalizing the reference mission definition and the elicitation of the system requirements. After that, the partners will perform the preliminary and detailed design of the different components of the system, including the required update and extension of the common building blocks. After the MAIT phase of the individual constituents and the development in parallel of the required software (simulation, frameworks, planning, execution and monitoring tools, and robot controller), the overall MOSAR setup will be installed for tests and demonstration in the laboratory facility of SPACEAPPS. In order to offer realistic lighting conditions, the environment will be closed with opaque separations and a lighting system (partially) representative of sun illumination (in the visible spectrum and possibly near IR) will be installed. The FES suite from DLR and the ERGO monitoring and control interfaces will be integrated in the Monitoring and Control center associated with the demonstrator.
This paper has described a new European Commission funded space robotic demonstrator project. After introducing three demonstration scenarios and challenges in achieving these, five common building blocks have be reviewed and additional functionalities analyzed and identified for these demonstrations. Preliminary spacecraft modules have been defined, a novel walking manipulator and the overall system modeling and simulation tool also introduced. Finally, a demonstrator design workflow is defined to guide the project team to work on the real implementation.

6. ACKNOWLEDGMENT

MOSAR is funded under the European Commission Horizon 2020 Space Strategic Research Clusters - Operational Grants, grant number 821996. The consortium, coordinated by Space Applications Services, includes DLR, GMV, Thales Alenia Space France, Sitael, Magsoar, Thales Alenia Space UK, The University of Strathclyde and Ellidis.

7. REFERENCES

[1] Small Spacecraft Systems Virtual Institute, NASA. State of the Art: Small spacecraft Technology. 2018.

[2] Muñoz Arancón, M., Montano, G., Wirkus, M., Hoeflinger, K., Silveira, D., Tsiogkas, N., Hugues, J., Bruyninckx, H., Dragomir, I., Muhammad, A. (2017). ESROCOS: A robotic operating system for space and terrestrial applications. *14th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA).* ESA.

[3] Ocón, J., Colmenero, F.J., Estremera, J., Buckley, K., Alonso, M., Heredia, E., García, J., Coles, A.I., Coles, A.J., Martínez, M., Savaş, E., Pommerening, F., Keller, T., Karachalios, S., Woods, M., Bensalem, S., Dissaux, P., Schach, A., Marc, R., Weclewski, P. (2018). The ERGO framework and its use in planetary/orbital scenarios. *69th International Astronautical Congress (IAC), Bremen, Germany, 1-5 October 2018.* IAC-18.D1.6.12x46215. International Astronautical Federation (IAF).

[4] European Cooperation for Space Standardization (ECSS). Space Engineering: Space segment operability. ECSS-E-ST-70-11C (31 July 2008).

[5] Fox, M., Long, D. (2003) PDDL2.1: An Extension of PDDL for Expressing Temporal Planning Domain, *Journal of AI Research 20 (2003)*.

[6] R.Dominguez, S.Govindaraj, J.Gancet, M.Post, R.Michalec, N.Oumer, B.Wehbe, A.Bianco, A.Fabisch, S.Lacroix, A.De Maio, Q.Labourey, F.Souvannavog, V.Bissonnette, M.Smisek, X.T.Yan. A Common Data Fusion Framework for Space Robotics:architecture and data fusion methods. International Symposium on Artificial Intelligence, Robotics and Automation in Space Symposia - Madrid, Spain, June 2018.