Space Robotic Systems and Artificial Intelligence in the Context of the European Space Technology Roadmap

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Abstract

This paper describes the activities of the German Research Center for Artificial Intelligence - Robotics Innovation Center (DFKI RIC) and its involved robotic systems SherpaTT and Mantis within the European Space Robotics Technologies Research Cluster (SRC) program. This program is divided into several phases which build on each other. Within this program, key technologies for space application were developed in five so-called Operational Grants (OGs) during the first phase. The program has two tracks, the orbital track aims at developing technologies for satellite missions, while the planetary track is focussed on planetary exploration operations, for example on Martian or Lunar surface. In a sixth OG, the technologies have been successfully demonstrated in an earth analogue mission for the planetary track and laboratory experiments within the orbital track. Currently running is the second phase with five further OGs. The outcomes of the first phase are summarized in this paper and the current activities within the second phase are presented. The focus is on the OGs PULSAR, ADE and PRO-ACT in which DFKI RIC is part of the respective consortium. This paper concludes with an outlook on the call for the third and final phase of the SRC program.

1 Introduction

The Robotics Innovation Center (RIC) is part of the Bremen office of DFKI, the German Research Center for Artificial Intelligence. Robotic systems for complex tasks in terrestrial applications, under water, and in space scenarios are developed at the RIC[1]. In contrast to "classical" robotic systems that were developed for planetary mission scenarios on Mars and Moon so far, the main goal of the space research at DFKI RIC is to develop new locomotive concepts paired with artificial intelligence in order to enhance autonomy of single robotic systems as well as to utilize the advantages of cooperative collaboration within heterogeneous multi-robot teams. Within such a cooperative collaboration, different mission scenarios on planetary surfaces can be performed. One possible mission scenario is a sample collection mission. The challenge here, among other things, is object recognition and localization. This requires solutions that use e.g. the generation of 3D point cloud images of the environment, the extraction of spatial entities from unorganized point cloud data generated by stereo cameras, range finders or other sensors suitable for point cloud generation [8], or the use of tactile sensors for haptic object recognition and localization [1].

Space robotics technologies have been identified as being key to increasing Europe's competitiveness in the space sector. Consequently, the European Commission deployed a Strategic Research Cluster (SRC) on "Space Robotics Technologies" within the H2020 research framework programme. With this SRC, the European Commission is funding the agenda-driven development of core technologies for a new generation of space robots with the aim of advancing the use of orbital systems and planetary exploration. The new technologies will be used to build modular and reconfigurable satellite systems as well as robots for the exploration of Mars, Moon, and other celestial bodies. The SRC implementation is supported by the "PERASPERA (ad ASTRA)" Programme Support Action (PSA). Together with the Commission, this PSA plans the strategic goals of the SRC on Space Robotics Technologies and oversees the implementation of the respective projects, or Operational Grants (OGs) [2].

DFKI RIC was involved in four of the six operational grants (OGs) funded in the first phase of the SRC. The objective of this phase was to develop a set of reliable and powerful technologies as building blocks for the next generation orbital and planetary robots. The first OG, ESROCOS, was designed to provide an open source framework that supports software development for secure, reliable and robust space robots. The use of open standards is intended to ensure the free use by research institutions and industry in order to accelerate the development and appli-

[1] Website of DFKI RIC: `https://robotik.dfki-bremen.de/en/startpage.html`

[2] Website of the EU project PERASPERA: `https://www.h2020-peraspera.eu/`

cation of new technologies and to avoid dependencies on specific manufacturers. The ERGO project (OG2) developed a software stack to support the decisional autonomy of the space robots. This included modules for mission planning, task planning, and execution. DFKI was not involved in OG2.

In OG3 InFUSE, DFKI scientists and partners developed a comprehensive data fusion framework specifically for applications in space. This framework offers a coherent collection of techniques for the fusion of sensor data, e.g. perception, localization and mapping data, in order to enable precise motion planning and navigation for robotic systems.

OG4 implemented a set of sensors that can be used as a module to enable enhanced environment perception for space robots. DFKI did not participate in this project.

The objective of SIROM (OG5) was to develop a standard mechatronic interface to connect payloads and other system components in both planetary and orbital applications. DFKI RIC co-developed the interface which is meant to facilitate satellite maintenance and the assembly of large structures, as well as the reconfiguration of planetary exploration rovers and construction of a modular planetary infrastructure. The interface not only establishes a mechanical connection, but also allows to transmit electrical energy, data and thermal energy between two modules.

The task of OG6 FACILITATORS was to provide the infrastructure (both robots, labs and outdoor test facilities) to test and validate the technologies developed in OG1 to OG5. DFKI RIC contributed to FACILITATORS by providing the SherpaTT rover platform (see also Section 2.1 and the Space Exploration Lab in Bremen. In addition, DFKI RIC organized an extended Mars analogue field test in Morocco.

The projects of the first phase of the SRC are terminated now. In the second phase of the SRC, five new OGs are funded. These projects started in February 2019 and will be terminated on the end of January 2021. DFKI RIC is involved in three of the five OGs: PULSAR (OG8), ADE (OG10) and PRO-ACT (OG11).

This paper gives an overview of the goals and results of the three second-phase OGs with DFKI involvement, describes the role of DFKI in these projects, and roughly outlines the other running OGs. Special emphasis is given to the two robotic platforms contributed by DFKI RIC, the hybrid walking and driving rover SherpaTT [5] and the six-legged walking system Mantis [3].

2 Robotic Test Platforms within SRC

In order to cope with upcoming space mission goals a need arises for capable robotic solutions, bringing together innovative technologies and software algorithms to provide reliable, highly integrated robotic systems with advanced autonomous behavior. The DFKI RIC has a traditionally strong background in the field of space robotics. Different robotic systems were and are being developed in the context of advanced space missions. The two systems set into place for the SRC program are the hybrid wheeled-leg rover SherpaTT and the six-legged walking robot Mantis.

Figure 1. Rover SherpaTT in planetary field testing in Morocco, end of 2018

2.1 SherpaTT

SherpaTT is a hybrid wheeled-leg exploration rover [5] as shown in Figure 1.

The active suspension system is composed of four legs ending in drivable and steerable wheels. SherpaTT allows six degrees of freedom body movements independent of the wheels' position. Additionally, a centrally mounted manipulator is used for handling payloads and modular containers in a multi-robot setting [17]. The arm further serves the purpose of locomotion support. A set of experiments concerning the locomotion performance of a hybrid wheeled-leg rover is published with [5], showing the system's high performance in terms of body angle control and active wheel-ground force distribution. The dimensions of SherpaTT are variable due to its active suspension system. The smallest foot print is taken in the so-called "stow-pose" with $1\,m \times 1\,m$. The biggest foot print is reached with $2.40\,m \times 2.40\,m$. Height ranges from $0.80\,m$ to $1.80\,m$, SherpaTT has a mass of $150 - 180\,kg$, depending on the payload configuration.

2.2 Mantis

Mantis was developed with the aim to provide high mobility and manipulation capabilities in uneven and unstructured terrain [3].

The operations of the system are focussed more on

Figure 2. Mantis in erected position by using its front legs for manipulation

complex manipulation tasks rather than in-situ investigation or sample collection. Typical tasks intended for the system are building up and maintenance of infrastructure which is required to support and sustain human presence on extraterrestrial bodies in future missions. Therefore, the robot possesses six extremities for locomotion, each having six active degrees of freedom. In addition, Mantis is able to erect its body and free the two fore-most extremities to use them as arms, both featuring three-fingered hands for dual arm manipulation and a bracket to walk on as shown in Figure 2. The main electronic compartment (power management, high-level processing and overall robot control) is located in the rearmost body segment, the abdomen. The abdomen further serves as a counterweight to the upper body and thus shifting the center of mass towards the frame articulation in the center of the four rear legs. This feature facilitates switching between locomotion and manipulation postures. The head and end-effectors of the extremities are equipped with various sensors to acquire data of the environment. The dimensions of Mantis are $2.96\,m \times 1.84\,m \times 0.32\,m$ (locomotion posture) with a mass of $107\,kg$.

3 Summary: Operational Grants from the First Phase (2017-2019)

In this section, the OGs of the first call and their major outcome are described. References to established websites and software repositories are provided. A video documentation of the results from the planetary track is available on youtube[3].

[3] `https://www.youtube.com/watch?v=-zqve9baOzM`

3.1 ESROCOS - European Space Robot Control Operating System (OG 1)

The European project “European Space Robotics Control and Operating System” (ESROCOS) [12] aimed to provide an open-source framework to assist in the development of flight software for space robots with space-grade Reliability, Availability, Maintainability and Safety (RAMS) properties. The resulting ESROCOS software system [2] comprises of different mature and novel tools with the TASTE software at its core and is developed by the consortium of following companies: GMV Aerospace and Defence (Spain), Deutsches Forschungszentrum fuer kuenstliche Intelligenz DFKI GmbH (Germany), Universite Grenoble Alpes (France), Katholieke Universiteit Leuven (Belgium), Airbus Defence and Space (The United Kingdom), Deutsches Zentrum fuer Luft und Raumfahrt DLR e.V. (Germany), GMVIS Skysoft (Portugal), Intermodalics (Belgium), Institut Superieur de l’Aeronautique et l’Espace (France) and VTT Technical Research Centre of Finland Ltd (Finland). TASTE [15] allows the specification and generation of correct-by-construction software for heterogeneous embedded systems. ESROCOS specializes the use case for TASTE for the needs in space robotics. It aims to establish a standard workflow and infrastructure for robot software development in the European space industry and – in the longer run – a pool of state-of-the-art software solutions for common algorithms, driver and tools needed in space robotic software applications.

TASTE comprises of tools for modeling, analyzing and compiling applications composed from multiple software components. A key feature of TASTE is the support of interactions of components on distributed and heterogeneous hardware platforms. Hence, control over data type modeling and serialization and cross-compiling capabilities in the build process are provided for a selection of hardware platforms relevant for the space domain.

With ESROCOS, several additions where made to TASTE. Figure 3 summarizes these additions. Component re-use capabilities were added by extending TASTE with features to im- and export component interfaces and source code. To allow for interoperability of software components that are developed independent from each other, a set of common data types (ASN.1 data types) for robotics applications were defined and are part of the ESROCOS framework. To support developers with distributing their software components, a mechanism for registering new software packages in the ESROCOS system and their automated retrieval from public source code repositories was added (collaborative development). The reusable software components pool was initially populated with components, that are of common use in robotics. Furthermore, a tool for the automatic derivation of kinematic solutions for robotic systems was added.

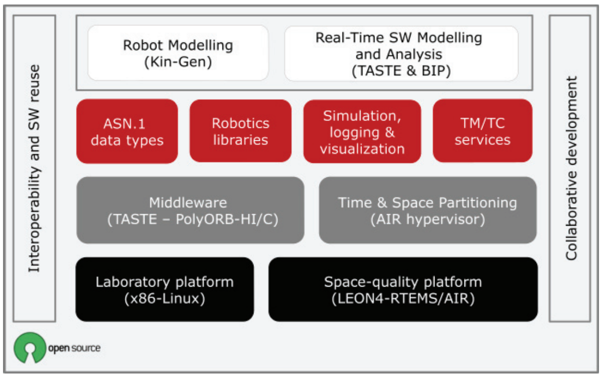

Figure 3. The ESROCOS Framework is built from different mature and novel tools [2]

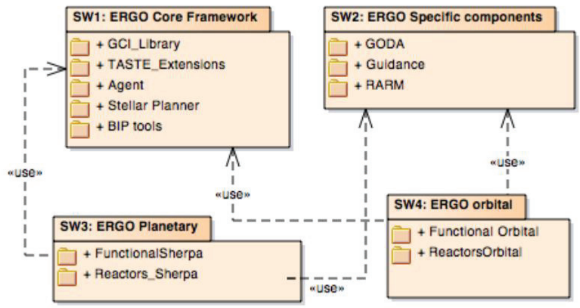

Figure 4. ERGO framework packages [14]

A feature unique to TASTE compared to other component development frameworks is the possibility to analyze the real-time behavior and resource utilization of the software. ESROCOS complements these capabilities with including the Behavior, Interaction, Priority (BIP) tool [4, 13]. BIP offers additional possibilities to analyze the software and verify properties at a behavioral level, and can be used to generate correct-by-construction software components by modeling their behavior as automata and translating them to executable code.

To validate the project results, three test campaigns have been carried out towards the end of the project in the second half of 2018. For each test campaign a different control application was implemented for a different robotic system including a commercial manipulator in an orbital scenario, a special purpose large-scale manipulator for a nuclear reactor, and a space rover in a planetary exploration scenario [19]. The individual test systems where provided by different companies or research institutes via the OG6-Facilitators (see 3.6) project.

More information about the project and results can be retrieved from the official project Website[4] or Developer documentation[5]. Most parts of the ESROCOS software are released under open source licenses and are made available on the project source code repository[6].

3.2 ERGO - European Robotic Goal-oriented autonomous controller (OG 2)

The European Robotic Goal-oriented autonomous controller (ERGO) is developed within the collaboration of following companies: GMV Aerospace and Defence (Spain), King's College London (United Kingdom), Universitaet Basel (Switzerland), Universit Grenobles Alpes (France), Airbus Defense and Space Ltd. (United Kingdom), Scisys (United Kingdom), Ellidiss Technologies (France) and GMV Innovating Solutions Ltd. (United Kingdom). As a framework, ERGO provides a set of components that can be reused and tailored for robots space missions (orbital, deep space or planetary explorations) in which the on-board system has to work autonomously, performing complex operations in hazardous environments without human intervention (see Figure 4). The concept of autonomy can be applied to a whole set of operations to be performed on-board with no human supervision, such as Martian exploration rovers, deep space probes, or in-orbit assembly robots. In the last decades, the advantages of increasing the level of autonomy in spacecraft have been demonstrated in planetary rovers. At the same time, orbital space missions have already successfully applied autonomy concepts on board, in particular for autonomous event detection and on-board activities planning. ERGO provides a framework for on-board autonomy systems based on a specific paradigm aimed to facilitate an easy integration and/or expansion covering future mission needs; by using this paradigm, both reactive and deliberative capabilities can be orchestrated onboard. In ERGO, deliberative capabilities are provided via AI techniques: automated planning and machine-learning based vision systems. ERGO also provides a set of tools for developing safety-critical space mission applications and FDIR systems. Moreover, specific components for motion planning, path planning, hazard avoidance and trajectory control are also part of the framework. Finally, ERGO is integrated with the TASTE middleware. All ERGO components were tested in a planetary scenario during the field tests in Morocco [14].

The user manual and sources for the ERGO software can be found on the official project website[7]

[4] ESROCOS Website: `https://www.h2020-esrocos.eu/`

[5] ESROCOS Developer Documentation: `https://github.com/ESROCOS/esrocos.github.io/wiki`

[6] ESROCOS on GitHub: `https://github.com/ESROCOS`

[7] User manual on ERGO website: `https://www.h2020-ergo.eu/wp-content/uploads/ERGO_D4_3_User_Manual_V2.0.pdf`

3.3 inFuse - Infusing Data Fusion in Space Robotics (OG 3)

Infusing Data Fusion in Space Robotics, in short inFuse, was an European project with the following companies: Space Applications Services NV (Belgium), Deutsches Zentrum fuer Luft- und Raumfahrt DLR e.V. (Germany), Deutsches Forschungszentrum fuer kuenstliche Intelligenz DFKI GmbH (Germany), Magellium SAS (France), University of Strathclyde (United Kingdom) and Centre National de la Recherche Scientifique (France).

During the project InFuse, the software building block for space robotics data fusion was designed, developed and tested.

Data Fusion concerns the combination of data originated in different sources (e.g. sensors, orbital maps, CAD models) to generate different data products with the characteristics required to achieve particular autonomous tasks. For instance, multiple pose estimations (e.g. from the integration of joint positions and from visual SLAM) can be combined to generate a highly accurate and fast updating position estimation of the robot. This position estimation is crucial, for instance, to achieve the task of reaching a location avoiding obstacles.

The main software outcome of the project is the open source Common Data Fusion Framework (CDFF). CDFF has been implemented following the guidelines recommended by ESA and other European Agencies regarding source code standards for the space domain. It provides standard interfaces designed to integrate in OG1 (ESROCOS) and a collection of perception functionalities. From these functionalities, a team of engineers involved in the preparation of a particular mission can take the subset which better matches the mission needs. Some of the functionalities included are: Visual SLAM, Pose Fusion, 3D Object Reconstruction from 2D images, Object pose estimation and Tracking. In addition to this, CDFF includes a set of development tools which can be used to evaluate prototypes using logged data, benchmark any data fusion component implementation or simply visualize the collected data and the generated data products in a mission [6]. A second outcome of the project are the planetary mars analog datasets [11]. During the test campaigns in Morocco datasets where collected with different robots in an environment with conditions similar to those found in Mars. These datasets can now be used by scientists and engineers to test their solutions.

The validation of the CDFF software was done in two tracks: one concerning the software developed for orbital scenarios and one for planetary missions. The orbital track was simulated using the On-Orbit-Servicing Simulator from the German Aerospace Center (DLR). The realistic images taken from one satellite approaching another were used to evaluate the performance of the tracking and object identification methods included in the CDFF. The planetary track final field tests were done in the desert of Erfoud (Morocco). The Handheld Central Robot Unit (HCRU), a sensor module produced by DLR, was attached to the robot SherpaTT as shown in Figure 5. The HCRU included representative sensors of the space domain (e.g. Cameras, Inertial Measurement Unit) as well as sensors for ground truth estimation (LIDAR and GPS). During the field tests data sets were collected and several data fusion performance tests were run (e.g. object tracking, object reconstruction, point cloud from stereo images).

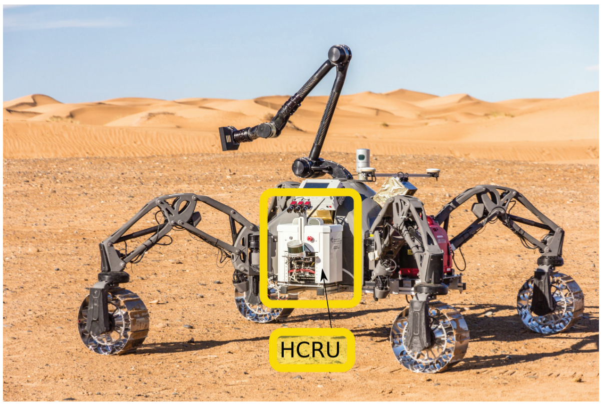

Figure 5. For validation tests and space analog data collection, the HCRU sensor module, engineered by DLR Institute of Robotics and Mechatronics, was mounted on DFKI's SherpaTT Rover.

3.4 I3DS - Integrated 3D Senssors suite (OG 4)

The I3DS project was aimed to realise a suite of perception sensors that allow localisation and map-making for robotic inspection of orbital assets and for planetary surface exploration. The key goal was to develop a harmonised and modular suite of sensors with common interface. The consortium included the companies Thales Alenia Space (France, Italy, Spain, United Kingdom), SINTEF (Norway), Terma (Denmark), Cosine Research BV (The Netherlands), Przemyslowy Instytut Automatyki i Pomiarow PIAP (Poland), Hertz Systems Ltd (Poland) and Cranfield Aerospace Ltd (United Kingdom).

In I3DS a new robotic spacecraft architecture was developed. INSES, an Inspection Sensor Suite composed of various and dedicated state-of-the-art sensors allowing the spacecraft to be aware of its environment and then to act accordingly by the real-time processing of the data coming from the sensors.

I3DS is a generic and modular system answering the needs of near-future space exploration missions in terms of remote and contact sensors with integrated pre-

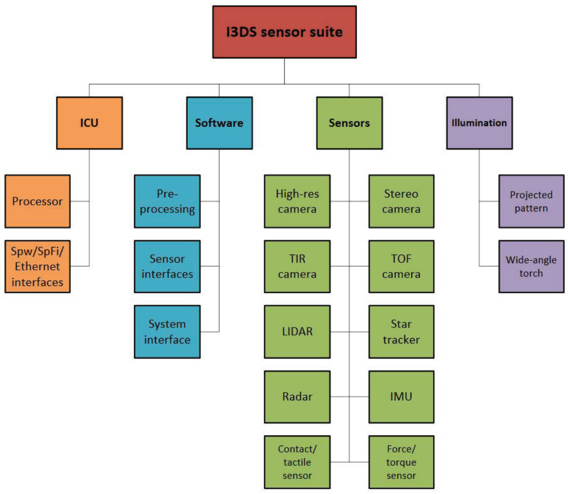

Figure 6. Product Tree of the I3DS sensor suite [10]

processing and data concentration functions. It consists in state-of-the art sensors and illumination devices integrated in a coherent architecture as inter-changeable building blocks and targeting a vast range of missions such as interplanetary missions, formation flying missions, non-cooperative target capture such as debris removal missions, cooperative rendezvous: servicing & spacetugs, landers, rovers etc.

The architecture of I3DS enables pushing the vision sensors as part of future exploration satellite platforms standard GNC units. It enables computing navigation solutions with on-board computers to be available for post-2020 missions autonomously from Ground. To do so, the data throughput provided by the sensors is pre-processed (filtering, compression, correction of distortions) by dedicated boards within I3DS. I3DS provides also an abstraction of the many electrical interfaces of the sensors by centralising the data flux using dedicated communication nodes. The mechanical interface is also simplified through the integration of the different sensors and boards in an integrated module. The I3DS design enables easy and low-cost configurations and reconfigurations of a robotic platform for any mission using the modular sensors.

The product tree shown in the Figure 6 describes the main components of the OG4 sensor suite exposed to the other OG's through the interface.

The sensor items in the product tree are:

- A star tracker for orientation and location by using the stars
- A time of flight (TOF) camera that captures depth images to generate 3D point clouds
- A stereo camera that delivers of two synchronized image streams that can be processed into a disparity map and 3D point clouds
- A high-resolution camera that delivers a monochrome image stream
- A thermal infra-red (TIR) camera that delivers thermal image stream
- Force-Torque sensors and contact sensors which deliver contact information with the target
- A light detection and ranging (LIDAR) that delivers distance measurements to generate 3D point clouds
- A radar used for ranging measurements
- An intertial measurement unit (IMU) that keeps track of the systems rotational and spatial acceleration

For illumination items the projected pattern illumination can be used with the high-resolution camera and a pre-processing algorithm to create 3D point clouds. The wide-angle torch provides general illumination when needed for both the high-resolution and stereo cameras.

The Instrument Control Unit (ICU) contains the SpaceWire networking equipment for connecting devices and high-performance Multi-Processor System on Chip (MPSoC) and FPGA for control of the devices, processing of data streams and interfacing with the On Board Computer (OBC) via SpaceWire.

The software components of the system are pre-processing of imaging streams, the sensor interfaces for controlling and accessing the sensors, the system interface for receiving commands and sending data to the OBC and the real-time operating system.

More information about the project and results can be retrieved from the official project Website[8]

3.5 SIROM - Standard Interface for Robotic Manipulation of Payloads in Future Space Missions (OG 5)

Within the Standard Interface for Robotic Manipulation of Payloads in Future Space Missions (SIROM) project following companies developed together a multi-functional interface (IF): SENER Ingenieria y Systemas S.A. (Spain), Airbus Defence and Space (United Kingdom), Airbus DS GmbH (Germany), Thales Alenia Space (Italy), Leonardo S.p.A. (Italy), University of Strathclyde (United Kingdom), Deutsches Forschungszentrum fuer kuenstliche Intelligenz DFKI GmbH (Germany), Teletel (Greece), Space Applications Services (Belgium) and Mag Soar SL (Spain). The capabilities of maximising standard payload modules functionalities for applications

[8] I3DS Website: http://i3ds-h2020.eu

such as on-orbit satellite servicing or planetary exploration depend critically on the creation and availability of a standard interface.

The SIROM provides, aside from the necessary mechanical interconnections, electrical power and data connections, as well as thermal transfer between building block payload modules. The overall flexibility allow a wide range of reconfigurations of payload and other modules for different functional requirements. The SIROM solution combines the four functionalities in an integrated and compact form with a mass lower than 1.5kg and having an external diameter of 120 mm and an external height of 30 mm. This novel IF permits not only mechanical coupling but also electrical, data and thermal connectivity between so called Active Payload Modules (APMs), as well as other modules such as robotic end-effectors. This multi-functional IF features an androgynous design to allow for replacement and reconfiguration of the individual modules in any combination desired. It consists of the following sub-assemblies: mechanical IF, electrical IF, data IF, thermal IF and IF controller (see Figure 7). A clear advantage of SIROM design is that its mechanical IF consists of a latching and guiding systems for misalignment correction, capable of withstanding certain robotic arm positioning inaccuracies: +/-5mm translation and +/-1.5° rotation in all axes. Regarding the electrical and data IFs, SIROM transfers up to 150 W electrical power and provides a data transfer rate of 100 Mbit/s via SpaceWire, plus command communication with speeds up to 1Mbit/s via CAN bus. The thermal IF provides fluidic ports for flow transfer and has the potential to transfer 2500W between APMs accordingly provided with the corresponding close-loop heat exchange system. Although not envisaged for SIROM current design, a possible variation could be to use these ports for satellite re-fuelling. Apart from that, SIROM exhibits redundant coupling capabilities: it can match and couple another completely passive SIROM. It is provided with main and redundant connectors for thermal, electrical, data and control flow in case of one of the lines fails. All in all, SIROM will enable long duration missions with no logistic support, refurbishing, maintenance and reconfiguration of satellites, cost efficiency and simplification of the tool exchange in scientific exploration missions. SIROM is designed to be a common building block for European and possibly world future space robotics enabled missions [18].

The SIROM was successfully tested within a planetary scenario demo and an orbital scenario demos within the FACILITATORS project. Descriptions and results can be found on the SIROM Website[9].

[9] D7.2 OG5-D0 SIROM Final Report in Dissemination on the SIROM Websitehttp://www.h2020-sirom.eu

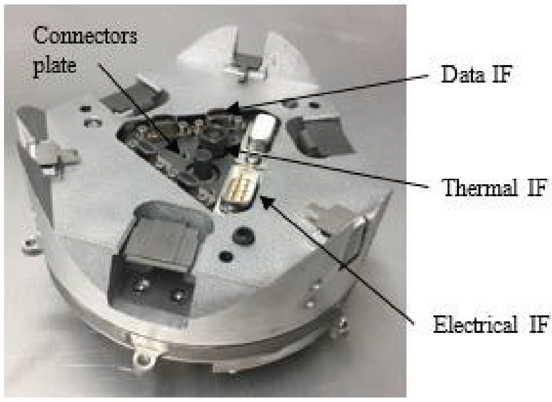

Figure 7. The SIROM interface [16]

3.6 Facilitators - Facilities for Testing Orbital and Surface Robotics Building Blocks (OG 6)

The FACILITATORS project provided the facilities needed to test and validate the technologies developed in OGs 1-5. The FACILITATORS consortium was lead by GMV Aerospace and Defence (Spain) and included partners from Germany (DFKI RIC and the Deutsches Zentrum fuer Luft und Raumfahrt DLR e.V.) and the UK (Airbus DS). In this consortium, DFKI RIC was responsible for supporting the tests in the planetary track. This included the provision of a laboratory environment and a robotic platform to support the tests of the standard interface developed in OG5 SIROM. It also included the organization and technical and logistic support of a Mars analogue mission in the Morrocan desert. Here, the sofware stacks developed in OG2 (ERGO) and OG3 (InFUSE) could be tested in a landscape similar to that of Mars.

As specified in the Grant Agreement, the main objectives of FACILITATORS were

- Enabling the highest possible level of validation of the common building blocks (that had been developed by the other operational grants) in the most relevant environment by adapting and providing the best available European test facilities needed by each technology or combination of technologies/domains (with minimal duplication of means and activities) and
- Guaranteeing coherence among the different test facilities and among the building blocks by establishing common implementation and validation scenarios (to be reproduced during ground testing) and common interfaces with the test facilities.

For the planetary track of the SRC operational grants, FACILITATORS organized an extended field campaign in a desert region in south-eastern Morocco between

Mid-November and Mid-December 2018 https://www.youtube.com/watch?v=-zqve9baOzM. The SherpaTT rover [5] provided by DFKI was used as the main platform to test the autonomy software developed in ERGO (OG2) and the data fusion and navigation software that was a result of InFUSE (OG3).

For almost four weeks, various tests and experiments were conducted. The objective was to ensure that the software stacks are able to perform as expected under the complex and harsh conditions of the Morocco desert environment.

Although the terrestrial desert analogue does only partially reflect true martian conditions, it is important for testing the exploration rover and control software. It combines numerous environmental conditions (e.g. changing lighting, fine dust, harsh terrain, significant changes in temperature, long distances to be traversed) which in the lab can only be simulated individually. This, together with the many unforseen challenges and obstacles that typically have to be overcome during an analogue mission, is what makes field trials a not only valuable, but necessary extension of pure lab-testing of systems or sub-systems.

In Morocco, the field trials culminated in a autonomous long-range traverse performed in a Mars-analogue desert terrain near the south-eastern city of Erfoud. Guided by the ERGO software, SherpaTT conducted a simulated sample recovery mission that sent it on a traverse through the hilly desert scape for more than 1,6 km.

4 Operational Grants from the current Second Phase (2019-2021

In the current phase of PERASPERA five new OGs are running. DFKI RIC is involved in OG 8 (PULSAR), OG 10 (ADE) and OG 11 (PRO-ACT). These OGs will be described in further details. A short overview in the next subsection describes OG 7 (EROSS) and OG 9 (MOSAR) in order to gain a more comprehensive impression of the goals and the consortiums in the current second phase.

4.1 European Robotic Orbital Support Services (EROSS) - OG 7

EROSS (European Robotic Orbital Support Services) objective is to demonstrate the European solutions for the Servicers and the Serviced LEO/GEO satellites, enabling a large range of efficient and safe orbital support services. The project will assess and demonstrate the capability of the on-orbit servicing spacecraft (chaser) to perform rendezvous, capturing, grasping, berthing and manipulating of a collaborative client satellite (target) provisioned for servicing operations including refuelling and payload transfer/replacement. EROSS embeds key European Technologies by leveraging on actuators, sensors, software frameworks and algorithms developed in previous European Projects. EROSS boosts the maturity of these key building blocks and increases their functionalities and performance in a coherent work programme targeting fast and practical deployment of the developed solutions in space. The consortium went into great details in the EROSS concept and the technical operational plan to manage perfectly the risks and complexity of development of such a large system. Following EROSS, Thales Alenia Space plans to commercialize its Multi-Purpose Servicing Chaser in 2021 for the LEO and GEO servicing business, pulling with him the projects technology providers. Besides, most partners will address other short-term space/non-space markets, such as Space Exploration and Science and factory automation (sensors, robots). The project success relies on a highly skilled and experienced consortium consisting of Thales Alenia Space (France), GMV (Spain), National Technical University Athens (Greece), PIAP Space (Poland), Sener (Spain), Sintef (Norway), Sodern Ariane Group (France) and Space Applications Services (Belgium)[10], [11].

4.2 Modular Spacecraft Assembly and Reconfiguration (MOSAR) - OG 9

The HORIZON 2020 EU-funded MOSAR[12] initiative will aim to raise the degree of modularity of 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. That will include:

- A set of re-usable spacecraft modules as part of a global eco-system. Each individual module will be dedicated to a specific function as control, power, thermal management, sensors. Once assembled, they will allow the full functionality of the spacecraft

- 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

- Standards robotics interfaces, providing mechanical, data, power and thermal transfer for interconnection between the modules, spacecraft and walking manipulator

[10] https://cordis.europa.eu/project/rcn/218707/factsheet/en

[11] http://piap-space.com/2019/05/21/project-eross-in-horizon-2020-programme/

[12] https://www.h2020-mosar.eu/

- A functional engineering simulation environment and design tool, offering assistance for modules design, system configuration and operation planning, with the support of multi-physics engine

As part of the EU Strategic Research Cluster in Space Robotics, MOSAR will build on and consolidate technological results of previous projects of PERASPERA and its operational grants. The consortium consists of following companies: Deutsches Zentrum fuer Luft- und Raumfahrt DLR e.V. (Germany), Ellidiss Technologies (France), GMV Aerospace and Defence (Spain), Mag Soar (Spain), Space Applications Services (Belgium), Thales Aleinia Space (France and United Kingdom) and Strathclyde University (United Kingdom).

5 PULSAR - Prototype of an Ultra Large Structure Assembly Robot (OG 8)

The primary goal of PULSAR (Prototype of an Ultra Large Structure Assembly Robot) is to develop and demonstrate key-technologies to enable the assembly of large orbital structures directly in space. The size of objects, which can be deployed in space as a single piece, is very limited by todays launch vehicles. Large structures, such as next generation space telescopes, thus rely on technology to enable in-space and on-orbit assembly. This process poses exceptional requirements in precision and autonomy while being subject to disturbances and uncertainties in a free-floating environment. The underlying use-case in PULSAR is the assembly of the primary mirror of a large space telescope. The mirror consists of modular tiles which can be stored in a single satellite. A robotic manipulator is used to handle the individual modules and to build the entire structure autonomously. The proposed mirror has a diameter of 8 meters and consists of 36 hexagonal tiles, each with a diameter of approximately 1.5 meters. The high requirements for positional precision, however, limit the maximum length of the manipulator to approximately 2 meters. This is due to the mechanical flexibility that are inevitable in longer manipulators. Hence, one of the key challenges in PULSAR is the assembly of a large structure with a manipulator that is significantly smaller. To overcome this problem, the manipulator workspace must be carefully designed and extended beyond the manipulator's reach. A key concept in PULSAR is the extended mobility by manipulating a sub-assembly of multiple connected tiles. This allows the indirect assembly of the outermost tiles without the need for the workspace to cover this area.

DFKI will demonstrate the assembly process with a representative manipulator workspace. For this demonstration, researchers at DFKI Robotics Innovation Center are developing a life-size mock-up of the spacecraft, capable of demonstrating the assembly process and simultaneous manipulation of multiple tiles. To fulfill this challenging endeavor, researchers at DFKI will develop and implement advanced robot planning and control functions. The demonstration will require handling payloads that exceed the limits of small robots. Instead of using a larger industrial robot, the PULSAR demonstrator will be set up in the large underwater-test-bed of DFKI's Maritime Exploration Facility in Bremen. The micro-gravity conditions that can be simulated there relax the weight restrictions on the manipulator and allow the use of a representative robot.

The consortium consists of eight partners from four member states and one associated state: Magellium SAS (France), Graal Tech (Italy), Swiss Center for Electronics and Microtechnology CSEM (Switzerland), Deutsches Zentrum fuer Luft und Raumfahrt DLR e.V. (Germany), Deutsches Forschungszentrum fuer Kuenstliche Intelligenz DFKI GmbH (Germany), Space Applications Services (Belgium), ONERA (France) and Thales Alenia Space (France). More information about the project and it's current status can be found on the official project website[13].

6 ADE - Autonomous Decision Making in Very Long Traverses (OG 10)

The overall goal of the project ADE (Autonomous DEcision making) is to develop a rover system suitable to increase data collection, perform autonomous long traverse surface exploration, guarantee fast reaction, mission reliability, and optimal exploitation of resources. Verification and testing of the technology in a representative analogue terrain are also part of the project.

The main objective is an autonomous long range navigation with high reliability. The ADE rover guidance receives the coordinates of a target location and then plans and executes a safe and efficient route to this location. It locally re-plans to visit new local target locations that were determined on-the-fly based on the analysis of sensor data. This enables the rover to seize scientific opportunities.

Furthermore, consistent data detection and the avoidance of missing interesting data is of interest in ADE. Promising environmental features will be detected by an Opportunistic Science agent. ADE includes two instruments that will generate observation conflicts to be solved by the Autonomous Decision Making Module (ADAM).

Autonomous decision making capabilities in presence of goal conflicts are tackled with the ADE project. Key component of ADE is ADAM. It is based on the tight integration and update of robotic technologies including the

[13] Website of project PULSAR: https://www.h2020-pulsar.eu/

outputs of the former EU projects OG1-OG4. ADAM will autonomously and safely modify the rover nominal plan in case it identifies interesting features or when environmental hazards are recognized. The modifications are conducted in compliance with system constraints, on-board resources and temporal restrictions.

With the demonstration in a representative environment, ADE will be tested incrementally with increasing complexity until a full representative analogue is reached.

The components ADAM as well as the ADE avionic system, represent a step ahead in technologies applicable to multiple scenarios. The ADE demonstrator represents a breakthrough with respect to the way rovers will explore unknown hostile environments, both in space and on Earth.

DFKI contributions to the project are mainly two: 1) provision of the SherpaTT rover for the field tests as well as support for the integration of additional hardware and 2) Provision of a validation toolset including a robotic simulator.

The simulator will be used for testing during development of the software components as well as during mission execution on the Ground Control Station. In the later case, the goal is to evaluate the risk of potential operations before sending the correspondent commands to the rover. This will be possible thanks to the dynamical generation of simulations -based on the available data of the current state of the mission. A similar validation process for the safe autonomous exploration of caves in planetary surfaces was presented in [7].

The following companies constitute the consortium of the project: GMV Aerospace and Defence SA (Spain), Joanneum Research (Austria), Thales Alenia Space (Italy), Deutsches Forschungszentrum fuer Kuenstliche Intelligenz DFKI GmbH (Germany), Trasys International EEIG (Belgium), Magellium SAS (France), Airbus Defence and Space Ltd (United Kingdom), University of Oxford (United Kingdom), King's College London (United Kingdom), Universite Grenoble Alpes (France), GMV Innovating Solutions Ltd (United Kingdom), Universidad de Malaga (Spain) and Universita Del Salento (Italy).

More information about the project can be found on the official project Website[14].

7 PRO-ACT - Planetary RObots Deployed for Assembly and Construction Tasks (OG 11)

The European Space Agency is preparing a mission to demonstrate the feasibility of In-Situ Resource Utilization (ISRU) on the moon. Through harnessing the resources that are available in space, such ISRU plants would serve as a source of water and oxygen, both being the foundation for human outposts, and for delivery of hydrogen and oxygen fuel to various locations in cis-lunar space. This will lead to sustainability in space exploration for robotic exploration, human exploration and for commercial purposes. Thus, the primary objective of PRO-ACT is to implement and demonstrate multi-robot collaborative planning and manipulation capabilities in a lunar construction context, focussing on: (1) enabling assembly of an ISRU plant on the moon and (2) partial assembly of a mobile gantry crane which can also be used for 3D printing building elements for assembly and construction of human habitats.

Towards these objectives, the PRO-ACT project[15] aims to demonstrate a novel approach of deploying multiple robots to work towards achieving common goals by cooperative goal decomposition, cooperative mission planning and execution of cooperative manipulation for transport and assembly of an ISRU plant and its supporting infrastructure [9].

DFKI will support the multi-robot collaboration within the planetary construction scenario with the six-legged robotic system Mantis. In addition, PIAP is providing the six-wheeled rover IBIS[16] that comes with a six degree of freedom manipulator.

For an efficient development process, PRO-ACT is integrating the outcomes of the previous OGs with minor adaptations and extensions. The use of the ESROCOS framework provides standardized interfaces and allows a homogenous implementation and integration workflow on both heterogenous robotic agents. ERGO is used for the Multi-agent planning with the reuse of the implemented generic arm controller and motion planner. Within PRO-Act, it is extended by a cooperative manipulation controller. Based on the I3DS sensor preprocessing with an improved ICU version integrated in each robot, the InFuse framework is used for sensor fusion to generate high-quality information for the ERGO controllers. In addition, a multi-agent cooperative mapping and localization is developed. In order to be able to exchange the type of end-effector to support diverse manipulation tasks, a standardized interface, e.g. SIROM, is utilized.

The cooperative manipulation and assembly challenge is ambitious and one of the first attempts to cooperatively build up infrastructure with heterogenous robots within space application background. The internal integration and testing phases as well as indoor and outdoor analogue demonstrations will provide plenty possibilities to evaluate the performance of multiple robots performing complex tasks. Thus, space agencies can use the outcomes of PRO-ACT as reference for performing trade-offs and

[14] ADE Website: https://www.h2020-ade.eu/

[15] https://www.h2020-pro-act.eu/

[16] https://piap.pl/en/tag/ibis-en/

estimating feasibility of future mission scenarios.

The PRO-ACT consortium consists of following companies: Space Applications Services NV (Belgium), GMV Aerospace and Defence SA (Spain), Przemyslowy Instytut Automatyki i Pomiarow PIAP (Poland), Centre National de la Recherche Scientifique CNRS-LAAS (France), City- University of London (United Kingdom), AVS added Value Industrial Engineering Solutions SLU (Spain), La Palma Research Centre for Future Studies SL (Spain), Thales Alenia Space (United Kingdom) and Deutsches Forschungszentrum fuer kuenstliche Intelligenz DFKI GmbH (Germany)

8 Conclusion and Outlook

DFKI RIC was and is involved, together with other leading European companies and research institutions, in the development of key technologies for space robotics, both for applications in-orbit and on planetary surfaces. The robotic systems SherpaTT and Mantis developed by DFKI RIC are used as hardware platforms to deploy and test the software and hardware modules developed in several of the operational grants that are part of the SRC. The first phase of the SRC developed the building blocks for secure, reliable and robust space robots. This included software for autonomy, a comprehensive data fusion framework, a generic modular inspector sensors suite with selected sensors, as well as a standard interface for modular and reconfigurable robotic systems. The results of the first phase of the SRC are currently integrated in the operational grants of the second phase to support specific application scenarios. This includes the necessary modifications, adaptations and enhancements of the building blocks. For the European space robotics sector, the long term vision for applications in the orbital track is focused on servicing, the reconfiguration of modular satellites, the assembly of large (infra)structures in space. The future of planetary track is long term autonomy, access to difficult-to-reach sites, and In-Situ Resource Utilization and robot cooperation for the construction of infrastructures on Moon and Mars.

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