Development of Key Technologies Towards New Robotic Tele-Operation Capabilities

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ABSTRACT

Robotic systems, either autonomous or tele-operated, are the cornerstone to enable space exploration and celestial bodies colonization in the next decades, with the Moon as the likely next step before Mars for robotic and human-robotic missions. Various challenging requirements separate us from these achievements: hundreds of kilometres mobility range; the capability to penetrate into permanently shadowed regions at temperatures close to absolute zero and absence of light; the capability of operating under complete autonomy, tele-operated from a ground control centre or interacting closely with the crew. These demanding needs are driving the efforts of designing, building and validating robotic technologies and architectures to be used in robotic precursor missions to de-risk the human ones.

1. INTRODUCTION

In this paper we present the technologies developed in ESA projects Eurobot Ground Prototype (EGP) [1] and METERON (Multi-Purpose End-To-End Robotic Operation Network): robotic architectural modularity, perception, navigation and manipulation capabilities and a distributed control system, focusing on the advantages and benefits which could be implemented in future robotic platforms by using a modular robotic systems management framework [2]. Finally, we will present how those technologies can support the wider scheme of a medium-long term technology development process that will enable the robotic precursor missions and the human-robotic missions envisaged in the 2020s.

2. MULTI-PURPOSE END-TO-END ROBOTIC OPERATION NETWORK

Under the leadership of ESA, a joint ESA/NASA/DLR design-study (with inputs from CNES and Roscosmos) was conducted in December 2009 to assess the feasibility of setting-up a Multipurpose End-To-End Robotics Operations Network (METERON) using the ISS [6]. The fundamental concept of METERON is one of an operator in orbit around a planet controlling robotic assets on the planetary surface (e.g. Moon, Mars). The definition phase that occurred following this initial study led to the establishment of a number of ground tests and in-orbit demonstrations (tests involving the ISS). The overall objective of these tests being to emplace a robotic network, both in physical terms and with respect to the required centres of expertise, and to culminate in an end-to-end in-orbit test operating robotic assets at an analogue site to be defined, termed Analogue-1. The individual tests themselves were defined to build up the network step-by-step, and to implement the lessons learned during one step, into the next. The network investigates three areas: communications, robotics and operations, looking at the concepts and technologies most suited to future human exploration involved in each, and the inter-relationship between them. To date, in addition to numerous ground based preparatory testing, a total of six in-orbit demonstration tests involving the ISS have been performed, two of which (OPSCOM-1 in 2012, OPSCOM-2 in 2013 and SUPVIS-E in 2015) involved the EGP being controlled from the ISS by ESA astronauts Alexander Gerst and Andreas Mogensen respectively. Current efforts are focused on ground-based preparation testing for the Analogue-1 end-to-end test in 2019 with either or both David Saint-Jacques

(CSA) and/or Luca Parmitano (ESA).

2.1. METERON Experiment SUPVIS-E

The SUPVIS-E test (supervisory control of the EGP) involved the tele-operation of the EGP located at ESTEC using the rover control software Eurobot fLIght cOntrol Station (ELIOS) installed on two laptops, from the ISS by Andreas Mogensen. The objective of this test was to evaluate rover operations in 'supervisory mode', where the EGP was instructed to perform a set of pre-defined activities on a lunar lander mock-up, located close to the EGP at ESTEC. This required Andreas to verify the status of the EGP prior to continuing with the next step in the operational sequence. In addition, a specific test objective was to evaluate the situational awareness provided to the crewmember via the video streams provided through ELIOS – from the EGP and lander mockup). A smaller 'surveyor rover' was operated from the ground to provide an additional view (video stream). Movements of the rover were also displayed on a map in ELIOS. The SUPVIS-E communications architecture is shown in Fig.1

3. EUROBOT GROUND PROTOTYPE

The EGP is a robot prototype aiming to assist astronauts in the construction, monitoring and maintenance of a Lunar or Martian outpost (Fig.2). It consists of a 4-wheeled rover platform with two 7DoF manipulators capable of automatically exchange end-effectors and it is equipped with a vision system [3] allowing environment mapping, localization, tracking and visual servoing [4].

Figure 2. EGP and Lunar Lander mock-up

Since its delivery in 2010, the EGP mobile and ground segments have been constantly upgraded and used in indoor and outdoor field test campaigns and experiments. In the recent years EGP became one of the testing robots for METERON experiments, in particular in OPSCOM-2 and SUPVIS-E. In SUPVIS-E, the EGP has been upgraded with new localization capabilities, TAS-I Robot Management Framework (RMF) [2] to enhance system modularity and a distributed robotic control station (Eurobot fLIght cOntrol Station, ELIOS) allowing the simultaneous monitoring and control of multiple robotic assets from distributed locations on Earth (ESTEC, ESOC, B.USOC) and Space (ISS).

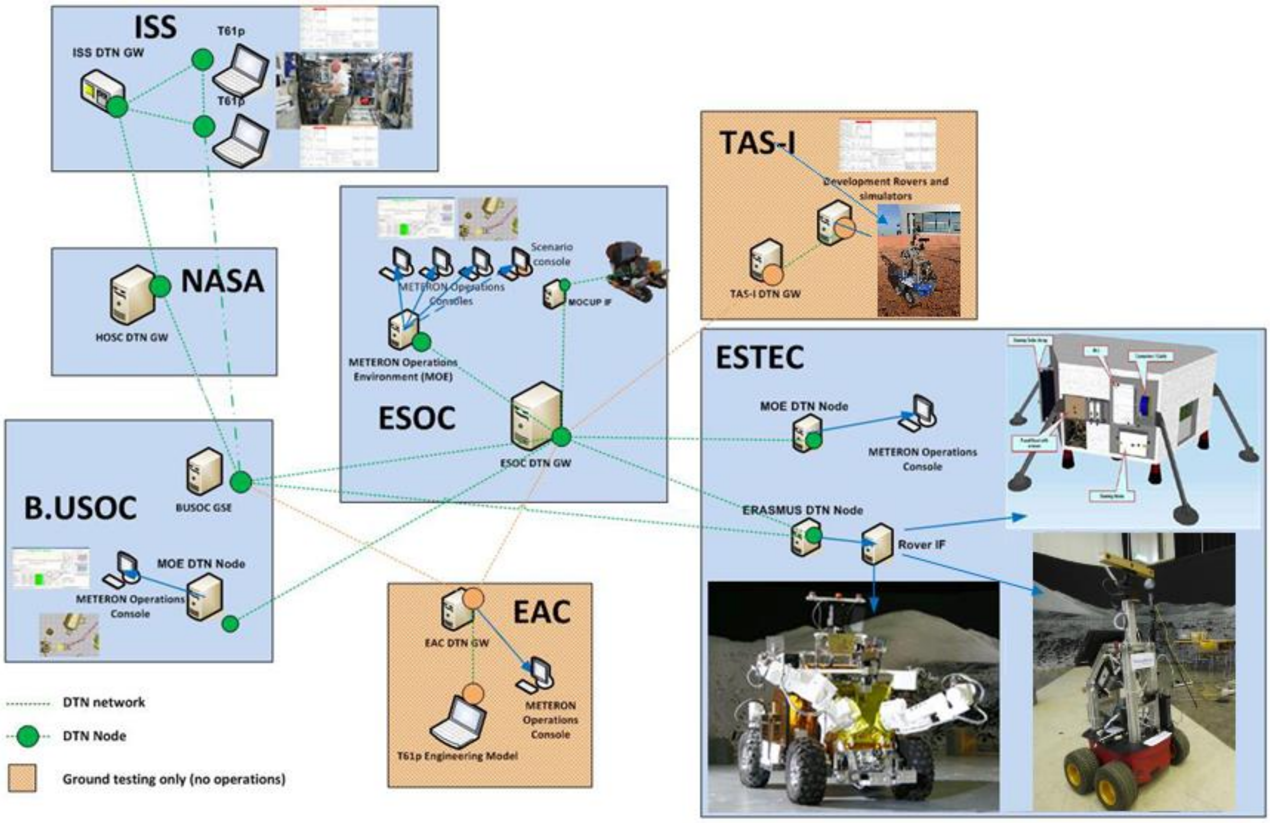

Figure 1. ISS and ground coordinating remote monitoring and control of multiple robotic assets over DTN

3.1. TAS-I Robot Management Framework

EGP is in fact an incremental system, where building blocks have been added over time, but without a modular architecture that could ease and ensure its upgrading in the long term (Fig.3).

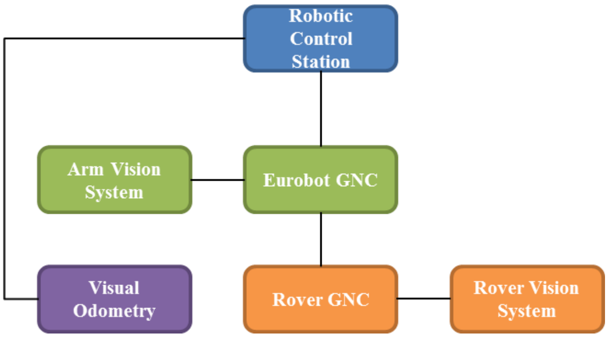

Figure 3. EGP original functional architecture

Adding new blocks usually lead to major modifications to other subsystems, increasing upgrade complexity. To recover from this issue, it was decided to deploy TAS-I robot management framework and customized modules to ensure that the many functionalities could be redistributed in simpler modules orchestrated by a software core, easing further upgrades in view of upcoming experiment and technology development (Fig.4).

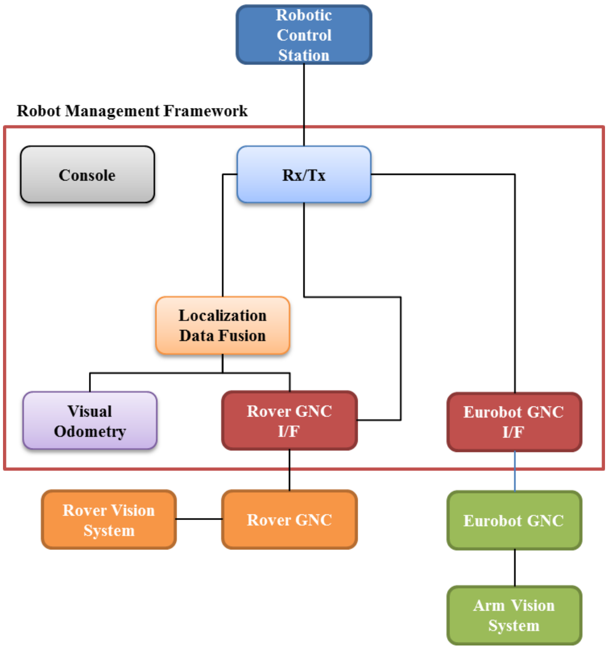

Figure 4. EGP functional architecture after upgrade

3.2. Autonomy and Human-Robot Interaction

The EGP implements many degrees of autonomy, from direct tele-operation to complex autonomous rover-arm coordinated control and Human-Robot Interaction.

The tasks implemented by the EGP include:

- **Environment Mapping:** based on stereo vision, the rover is capable of building a map of the environment and merging subsequent maps [3];
- **Relative Localization:** based on data fusion between mechanical, inertial and Visual Odometry sensors, ensuring high accuracy and precision [5];
- **Absolute Localization:** the rover vision system has three absolute localization modes based on stereo vision and markers: 1) automatic with coloured markers, 2) automatic with b/w markers and 3) manual where the control station operator can manually select fiducial markers on the lander structure where the algorithms are not able to automatically estimate the 6DoF pose of the rover w.r.t the lander.
- **Manipulator Control:** in Joints and Cartesian space;
- **Manipulator Force/Torque Control:** with the capability of automatically performing complex tasks such as extracting and installing ORU, opening MLI covers and sliding panels;
- **Manipulator Haptic Control:** to perform installation of ORU, maintenance activities and samples pick-up from remote using visual and force feedbacks;
- **Visual Servoing:** to perform fine alignment to reference markers enabling automatic grasping of handles, mating connectors and other precision tasks;
- **Rover-Arm Coordinated Motion:** with the capability of deploying a solar array mock-up and relocate a large box in cooperation with a crew in EVA.

4. EUROBOT FLIGHT CONTROL STATION

The Eurobot Flight Control Station named ELIOS was designed with the objective to comply with the main needs of the tele-operation concept described in paragraph 2. Its key features are:

- *Distributed deployment*: the control station can be deployed on nodes both on ground and in space. This is crucial to support tele-operation scenarios where astronauts in a space outpost are involved in the tele-operation process.
- *Delay and disruption tolerance*: in order to allow control nodes to be distributed across space, the software has been designed from the ground up to use the disruption tolerant networking (DTN) protocol.
- *Flexibility*: generic and configurable protocols are used to abstract robotic assets interface details which are only known to a specific node named HERMES, this allows to plug and play new control station nodes when needed without requiring a reconfiguration. In addition, a mechanism to manage the control dynamically during the mission has been implemented in order to enforce a single point of control with the possibility to change as needed.

4.1. Functional breakdown and software architecture

The functionalities which are provided by the software are:
- Telemetry reception and presentation
- Tele-commands creation and dispatching.
- 2D map navigation, path planning and visualization,
- Multiple video streams visualization
- Networking status visualization.
- METERON Messages reception and visualization
- Command history visualization
- Command stacks creation and dispatching
- Overlay commands on video stream visualization
- Rover state machine visualization and control
- Manual interactive localization procedure

Architecturally, the software is composed by the elements shown in Fig.5 This structure reflects in a one-to-one way the functional needs required for the software. The application layer implements the application logic which is visualized by the presentation layer. The network layer implements a network abstraction layer which abstracts two different communication stacks effectively decoupling them from the rest of the application.

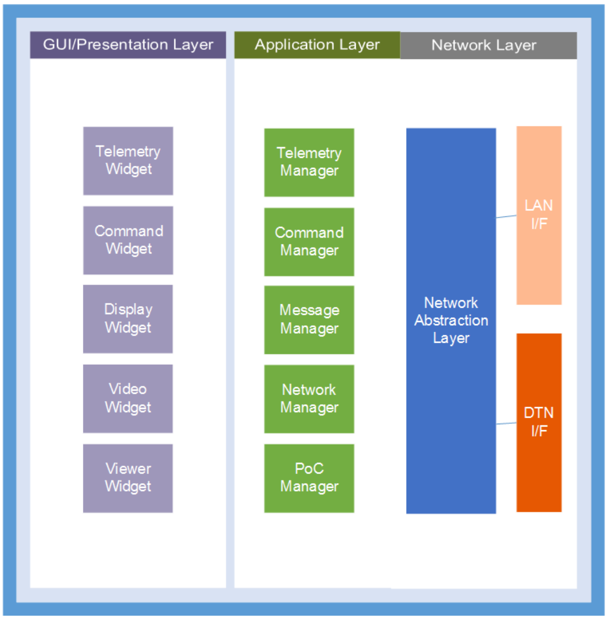

Figure 5. ELIOS functional architecture

4.2. Man-Machine Interface

The control station interface has two main views: the *flight view* and the *video view*. The flight view (Fig.6) is a comprehensive view which shows the most important widgets at the same time.
The video view (Fig.7) allows the visualization of only the 6 video players with the possibility to resize and move them in the screen.

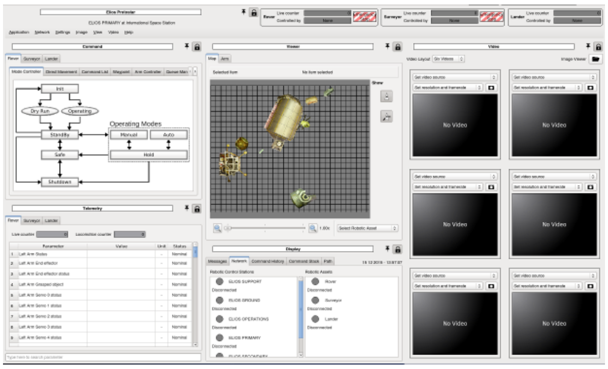
Figure 6. ELIOS flight view

This view has been conceived mainly for monitoring purposes and was used in a double deploy configuration on the ISS to provide an additional awareness of the surrounding environment to the astronaut.

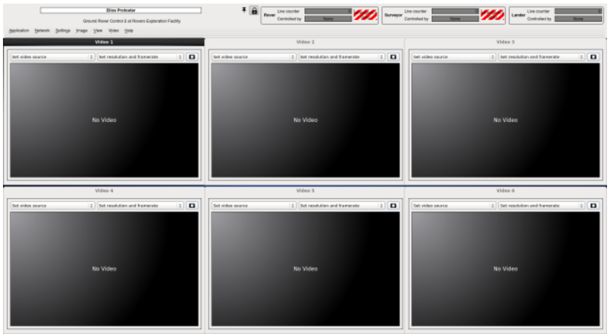
Figure 7. ELIOS video view

The main components of the interface are:
- Command widget: allows the operator to send commands for the tele-operated systems. It provides one tab per robotic asset and each tab has sub-tabs for specific functionalities.
- Display Widget: is the GUI element in charge of displaying a summary of basic information and every message incoming in ELIOS and outgoing from ELIOS. The Display Widget is organized in tabs and provides relevant insights on the mission.
- Application Bar: provides drop-down menus for the main ELIOS functionalities, displays basic information of the robotic assets and hosts the Emergency Stop buttons for each robotic asset.
- Telemetry widget: shows telemetry information of connected platforms in a tabular format.
- Video Widget: shows video streams to the operator. At startup, when ELIOS is not yet registered to any stream, the widget looks as depicted in Fig.6.
- Viewer Widget: is a 2D visualizer that displays the experiment scene and the platforms movements. to the operator. At startup, when ELIOS is not yet registered to any stream, the widget looks as depicted in Fig.7.

4.3. Communications

The responsibility of the network layer (Fig.5) lies in a set of methods which allow instances to communicate with each other, abstracting the details of the implementation of the communication stack. The protocol stacks supported are TCP and UDP over IP and the Delay Tolerant Network (DTN) stack. DTN is a network architecture that addresses the technical issues relevant to lack of continuous connectivity, such as in space. The principal communication protocols belonging to the DTN stack are the Licklider Transmission Protocol (LTP) and Bundle Transmission Protocol (BTP) or Bundle Protocol (BP). These provide the basis to all functionalities currently implemented in the software. The specific implementation of DTN used in METERON is the Interplanetary Overlay Network (ION) [6] developed by the Jet Propulsion Laboratory (JPL).
The latter is the protocol stack of choice in the context of METERON SUPVIS-E. Indeed, its features are a paramount when connecting multiple nodes across space through unreliable communication links.

5. TECHNOLOGY REUSE

The approach to EGP modularization discussed in 3.1 can be adopted to enhance other robots modularity and capabilities, relying on the TAS-I Robot Management Framework. It is possible to implement new and enhance existing functionalities relying on state-of-the-art libraries and algorithms at reduced effort in terms of costs and implementation time with respect to non-modular and less portable technologies. The framework gives also the flexibility to use it at system or subsystem level (i.e. only for navigation), thanks to portability to different operating systems and the communication libraries that can be easily integrated to support new protocols (i.e. DTN and DDS) and integration with other robotic frameworks (i.e. ROS).
The capabilities implemented and extensively tested in EGP, from haptic tele-operation of the robotic arms to astronaut following, coordinated robot-arm control and autonomous navigation (and the extensive documentation in accordance with ECSS), can be used as starting point for the enhancement of a new robotic platform to support the technology development of advanced functionalities. It is already under study how to implement these functionalities as modules on different platforms either using RMF (at system or subsystem level) or eventually relying completely on other robotic frameworks.

6. FUTURE ACTIVITIES

In addition to the tests involving the EGP, other METERON tests have been published [7][8][9][10]. The techniques and technologies and lessons learned from these tests will also provide inputs to the Analogue-1 activity, that currently has a human-assisted robotic lunar sample return mission as its reference mission scenario. The current planning foresees the following steps:

1. A joint analogue test with CSA (in Canada) scheduled for late September 2017.
2. Preparation for an analogue test in November 2018 coordinated with the European Astronaut Centre LUNA and PANGAEA activity that trains European astronauts in the identification of planetary geological features for future missions to the Moon, Mars and asteroids. Robotic-assisted geology will be a focus of the METERON involvement.
3. Participation in the PANGAEA activity in November 2018, most likely at an analogue site in Lanzarote.
4. A complete end-to-end test involving control of the robotic asset from the ISS in summer 2019 at an analogue site to be selected.

The conduction of these activities in preparation for Analogue-1 would involve:

1. Operation of a 'crew surrogate' centre based at EAC in Cologne.
2. Development and testing of a ground demonstrator and in-orbit demonstrator of a Robotic Human-Computer Interface (HCI).
3. Upgrading and testing of a new Exploration Ground Prototype rover/robot.
4. Robotic Testing in laboratory and at analogue sites at CSA in Canada, EAC, and in Lanzarote.
5. Further development, consolidation of Mission Operations & Ground Segment for Analogue-1.
6. Further development, consolidation and Operation of a Rover Operations Control Centre at CSA for the first test, at ESTEC for the PANGAEA activities and at to be selected location for Analogue-1.
7. Lunar Scientific Operations at the CSA site, and distributed thereafter.

For the tests planned for the future, leading to Analogue-1, the EGP rover/robot will likely be replaced by the modified Interact rover/robot [11], as it more closely matches the robotic lunar sample return scenario that will be investigated.
The experience gained from the utilization of the EGP in the METERON suite of ground-based and ISS tests has resulted in a wealth of lessons learned, particularly with respect to the rover/robot software architecture, flight control software and use of DTN, that may be potentially applied in the remaining activities up to and including the Analogue-1 test in 2019.

7. CONCLUSIONS

The technologies developed in the frame of Eurobot and METERON projects have been proven as highly reliable in the 8 years of exercise of EGP, allowing the successful implementation of laboratory tests, field test campaigns and ISS Robotic Tele-Operations Experiments. Leveraging on the lessons learned by designing, building, upgrading and operating such a complex robot over many years, the EGP functionalities can be ported to other robotic platforms (using modern SW engineering approaches, robotic framework and algorithms) and extended to support medium and long term technology development processes, from ground prototyping to a real mission involving robots, orbiting crew and ground control centres as foreseen by many envisaged future Moon exploration mission concepts.

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