Autonomous Decision Making: a key for future robotic applications

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ABSTRACT

Future space missions are facing new challenges that need to be overcome for applications like planetary exploration, in-site resource utilisation, deep-space probes, or Earth observation. They require higher levels of autonomy, based on smart machine decisions and advanced environment interaction without human intervention. A hierarchy of autonomous capabilities is needed, to turn robots into intelligent agents, able to collaborate.

In the last years, GMV has been developing an architecture for autonomous capabilities, whose cornerstone was ERGO, a project part of the PERASPERA SRC programme of the European Union.

ERGO has been reused in multiple projects, like ADE (Autonomous DEcision making in very long traverses).

Building on the ERGO experience CISRU, is meant to tackle AI-enabled complex robot-robot and robot-human applications to fuel-up In-situ Resources Utilisation scenarios for Moon and Mars exploration.

This paper discusses the objectives in these projects for autonomous systems as well as its conclusions and achievements.

1 AUTONOMY AS A COMBINATION OF CAPABILITIES

The autonomy of a spacecraft or robotic asset is the result of the interaction between different layers or components, each providing different capabilities to make possible complex and safe interactions with its environment. The specific functionalities in play depend on the characteristics of the mission and its environment. We find the following semi-autonomous capabilities:

Autonomous mapping and localisation, allows the system to perceive the surrounding environment, build local navigation maps during traverses and localise itself using its own sensors. Visual-inertial navigation is the current state-of-the-art approach, although other terrestrial paradigms are being transferred to the space domain, using technologies such as LIDAR [1] [2] or the novel deep learning approaches [3] [4]

Autonomous guidance guarantees that the system can traverse autonomously from point A to point B, identifying the path to be followed (path planning), driving through the selected path (trajectory control), and avoiding any possible obstacle on its way (collision avoidance).

Autonomous manipulation uses devices like robotic arms to manipulate samples. Sampling-based motion planners developed in 1990s allowed solving the motion planning problem in higher dimensions in reasonable time. This was particularly important for robotic arms. The seminal algorithms are probabilistic roadmaps (PRM) published by Kavraki [5] and rapidly exploring random trees (RRT) published by Lavelle and Kuffner [6].

The above-mentioned autonomous mapping, guidance and manipulation capabilities have been put in place in existing rovers for planetary missions like MER [7] [8], Curiosity [9] and Perseverance [10].

With respect to guidance, the mobility capability of rovers is limited. The distance travelled in one sol is relatively short (covering distances around 50-150 m), mainly due to limited on-board processing resources, the locomotion system, power storage capabilities as well as the limited ability to take decision on-board.

With respect to manipulation, in 2001, the Canadarm2 was added to the International Space Station (ISS) [11] and the European Robotic Arm (ERA) provides higher level of autonomy for proximity operations [12] and can walk on the Russian segment of the station. Mars Exploration Rovers Spirit and Opportunity as well as Curiosity are equipped with a robotic arm as also Chinese lunar rover Yutu. Curiosity features on-board autonomy and on-board motion plans [13]

Although these autonomous perception, guidance and manipulation capabilities are critical aspects that need to be improved, *there are higher level autonomous functions needed to achieve a full autonomous system*, these are:

On-board mission planning and scheduling, which uses automated planning technology onboard, combined with a scheduler or robotic controller. Automated Planning (AP) is the field of Artificial Intelligence (AI) that aims to provide computers with the ability to automatically generate plans that starting from a certain initial state reaches another state where some goals are achieved. This on-board planner can decompose high-level commands (i.e. “explore area”) into lower-level actions (go to points A, B, C, D, build the map of the area explored, finish at E, and downlink this map to ground). An on-board scheduler takes as inputs the actions from the planner and requests their execution using lower-level autonomous capabilities. A robot with the on-board mission planner/scheduler mentioned before can be considered as an “autonomous agent”, as defined in [14], “a system situated within and a part of an environment that senses that environment and acts on it, over time, in pursuit of its own agenda and so as to effect what it senses in the future”. It follows the so-called “Sense-plan-act” paradigm (SPA) and the robot can be commanded by using high-level goals. This highest level of autonomy is defined in the ECSS standards as E4 – “goal commanding” [15] . That same standard defines lower levels of autonomy, such as E3 commanding “adaptive” (also called event-driven) in which on-board procedures can be executed based on events, E2 “time-tagged” in which commanding is performed via time-tags and E1, in which only direct tele commanding is allowed. It is interesting to note that, as of today, none of the space missions has used E4 level of autonomy.

On-board scientific detection maximizes the scientific outcome of a mission by searching for and eventually identifying scientific targets. In general, we distinguish between two kinds of scientific targets: known classified targets and novel targets. An on-board scientific detector using AI techniques can detect both known classified classes and novel targets from images taken with cameras. The combination of a scientific detector and an on-board planner can be used to perform opportunistic science without having human in the loop. Scientific detectors usually use a Neural Network **[16]**; the neural network is trained: supervised training is performed for classified targets while unsupervised training is used for novel targets. The scientific detector can be considered as an extension to the Perception System, that applies AI techniques to detect targets of interest.

Autonomous safe operation allows the system to operate for as long as possible while ensuring a robust and reliable behaviour. Such capabilities are usually achieved through fault detection, isolation and recovery (FDIR) subsystems, both at mission and at subsystems’ level, by monitoring the system and environment states, detecting harmful situations and reacting accordingly to defined scenarios.

Autonomous robot cooperation and collaboration: aiming to have different robots being able to collaborate and/or cooperate to fulfil a different task. The team of robots becomes a multi-agent system (MAS), that is “a group of interacting agents working together to achieve a set of goals” [17] in which each agent must be able to reason about other agents' actions in addition to its own”. MAS architectures can be hierarchical or fully distributed, depending on the manner the intelligence of the system is grouped.

2 THE ERGO LEGACY

The roots of the autonomous capabilities that GMV has been developing in the last years can be found in the ERGO [18] project, an activity developed in the first call of the PERASPERA SRC [19] aimed to develop the basic building blocks for bringing intelligence and autonomy to space robotic applications.

The above-mentioned autonomous capabilities (except those related to the perception and localization system and multi-agent) were developed and tested in ERGO. Leading a large European consortium, GMV and its partners developed a set of components able to provide autonomous capabilities and tested them in two demonstrators for planetary and orbital scenarios [20].

ERGO was built using the TASTE toolset (the middleware chosen by the ESROCOS framework [21]). TASTE was in fact the “glue” that linked all these elements, allowing us to use a model-driven approach in which the code for the interfaces among the different components was automatically generated from models. We combined TASTE with the formal verification and validation techniques provided by the BIP tools [22][23] that were used in for developing FDIR components.

For the planetary scenario, ERGO used the SherpaTT rover [24] , which already had its own perception and localization system. Planetary field tests were conducted with the SherpaTT in a Mars Analog located in Gare Meduar (Morocco)

The orbital use case was aimed to an in-Orbit Servicing mission, where a damaged spacecraft can have one of its modules replaced autonomously by a servicer spacecraft. GMV used for this scenario an UR5 robotic arm [25] running in Platform-Art testing facility [26].

ERGO provided a hierarchy of autonomous capabilities, starting from the highest to the lowest we find:

On-board mission planning and scheduling Stellar [27] an on-board mission planner, was designed and delivered specifically for space missions, and developed by the King's College of London. This planner was complemented by an onboard executive (scheduler) developed by GMV. The combination of the planner and scheduler allowed to perform **onboard dynamic planning and replanning.** The planner allowed mission operations to be performed using goal commanding (E4) mode. Other modes of commanding (E1, E2, E3) were also possible. This planner was used in both the planetary and the orbital scenarios.

A **scientific detector,** GODA [27] developed by SciSys, allowed the system to perform *opportunistic science* in the planetary scenario.

Autonomous safe operation was guaranteed by using formal verification and validation techniques based on the BIP tools for FDIR components

Autonomous Guidance: a Guidance System, developed by Airbus [28] , demonstrated that the system was able to traverse autonomously hundreds of meters in a sol, using SLAM based on LIDAR and IMU. The SherpaTT Rover, equipped with ERGO specific SW and HW, was able to traverse more than 1 km in a day.

For **Autonomous manipulation**, GMV developed a Robotic arm library, based on RRT (Rapidly exploring Random Tree) that was used both for the SherpaTT (allowing pick and drop operations) as well as in the orbital use case.

The set of tools developed in ERGO were designed in such a way that they could be used together (as they were in the ERGO demonstrators) or separately.

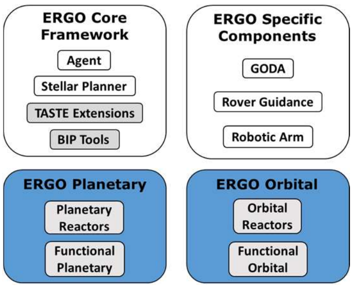

Figure 1. The ERGO Framework packages

As of today, ERGO has been reused in most of the projects of the PERASPERA SRC of the 2nd call, (namely MOSAR [29], PRO-ACT [30], ADE [31] and EROSS [32]), and is being used in the ongoing projects of the 3rd call (EROSS+ [33], PERIOD [34] and Corob-X [35])

3 ON-BOARD DECISION-MAKING: ADE

ADE was a project of the 2nd call of PERASPERA SRC. Since the objective of the different projects of this call was to reuse the so-called "building blocks" of the 1st call of PERASPERA, ADE was developed reusing ERGO as well as the perception and localization system from INFUSE [36], the framework for sensor management developed in I3DS [37] and the robotic operating system developed in ESROCOS.

3.1 ADE Objectives

ADE had two main objectives: to develop a demonstrator for an autonomous planetary exploration capable of long traverses, and yet another demonstrator to test the validity of this concept for a terrestrial scenario, aimed to nuclear decommissioning. The core of ADE was the so-called "ADAM" (Autonomous Decision-Making System), a HW/SW module that contained both the HW (sensors, actuations, processors, and dedicated electronics), and the SW (based on the mentioned building blocks, tailored to the uses cases, and refined with extended performances) for the autonomous capabilities mentioned in § 1, except robot collaboration and cooperation.

ADE included the development of a complete ground station capable of managing all modes of autonomous operation: direct tele commanding (E1), time-tagged (E2) event-driven (E3) as well as goal commanding (E4) operation. The ADE ground station was required to work in combination with the robot simulation, so that all three modes of operation were possible: simulation mode, real-execution mode, and replay mode. Ground Control integrates a mixed-initiative approach that allows to compute, modify, and validate on-ground the plans that will be executed on-board. The resulting ADE system was formed by three elements: the ADE ground station, the ADAM system that commanded the rover platform (with two different platforms used for the planetary exploration, and the nuclear use case) and the rover simulator

3.2 ADE planetary scenario

The ADE planetary scenario aimed to showcase the capability of traversing 1km in a sol with an error in the localization of less than 1.5 % with respect to the travelled distance. The developed demonstrator used the components mentioned before. The ADAM component provides the following autonomous capabilities:

On-board mission planning and scheduling was provided via the ERGO agent, that was tailored for the scenario. High level goals for the planner covered the traverse to a certain pose, gathering science via images at a certain pose, taking and moving samples between different locations and scanning an area for events of scientific interest. Tests were focused on the plan computation time, plan quality, handling of *soft goals* (goals that are not mandatory to be achieved), and the *oversubscription problem* (a large number of goals to be planned is requested and an optimal subset has to be found and planned).

The deadline for the planner to generate a new plan was 10sec, and it was only exceeded in 1 occasion, with an average time for plan generation of 0.23sec.

The mission success, defined as the number of goals achieved over number of goals planned, is roughly 15%, ranging from 36% without scientific detection to 0.09% with only scientific detection.

Opportunistic Science was provided by a scientific detector from the Oxford Robotics Institute that looks for events of interest from high-resolution images. It posts new goals for the planner, hence performing serendipitous science. The agent filters the events so that only those deemed relevant, or novel (based on a confidence score) are further inspected. Tests were focused on the novelty detection and correct planner-scientific detector interaction. This component analysed 78 images from which generated 44 events of interest that were further planned by the agent. In total there were 111 goals handled by the agent, with 10 of them correctly achieved. Further details on the performance of the scientific detectors can be found in [38]

Autonomous guidance, based on an improved Guidance from the ERGO framework [39]. This component was able to drive the rover in a traverse of 486 meters in less than three hours (2.86h). The rover achieved an average speed of 4.72cm/sec, moving for 65% of the test time and being idle for the remaining 35%, detecting 22 hazards and replanning the trajectory 11 times. A specific test of a single traverse of 1km in 6h was not achieved due to difficulties with the environment and stability of the system; further details are provided in [39]. Figure 2 shows the map of the 486m traverse.

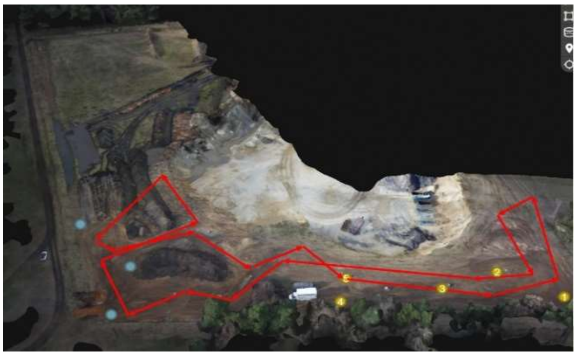

Figure 2. SherpaTT traverse of 486m during the field tests in Wulsbüttel (Germany)

A**utonomous mapping and localization** with stereovision based on the InFuse and I3DS frameworks, that were improved by Magellium and integrated into ADE. Perception and localization fulfilled the 1,5 % requirement, achieving an accuracy error of 0.4%, for the traverse of 486 meters. [39]

Autonomous manipulation via a dedicated and newly component developed by UMA, the combined mobility component that allowed the rover to perform robotic arm operations, by moving both the robotic arm and the rover platform jointly and choosing the point from which the sample should be approached. The combined mobility tests were successful, with the full sequence of operations performing nominally in all tests.

FDIR capabilities through a dedicated component tailored for the scenario and the desired requirements, built the BIP framework from ERGO. FDIR was also successfully validated.

3.3 ADE nuclear scenario

The ADE terrestrial scenario aimed to showcase the autonomous capabilities for nuclear decommissioning. More specifically, the following autonomous functionalities have been achieved:

- Autonomous 3D mapping of the plant by the rover, that provides information about the layout of the plant without staff having to enter hazardous (due to radiation) areas.
- Radiological characterization on an area of the plant during the same mapping.
- Detection of hot spots (i.e., identification of high-level radioactive areas when a threshold it is exceeded) and detection of water spills.

Additionally, the demonstrator included on-ground capabilities to plan the schedules of the workers dismantling the plant such that the radiation levels they are exposed to are minimal, as to gather and display the obtained products (map of the plant with the radiation level at the point where it was measured) for assessment.

The demonstrator uses the following components:

On-board mission planning and scheduling handling the functionalities listed above as high-level goals through a tailoring of the ERGO agent.

Opportunistic science through the same scientific detector used in the planetary scenario. In this case its neural network was trained to identifying water spills in high-resolution images.

Autonomous guidance available from the robotic platform for 3D mapping and radiological characterization.

Autonomous mapping and localization also available from the robotic platform based on LiDAR.

Autonomous manipulation: the robotic arm operations covered the radiation measurement (for characterization and hot spot detection).

The validation of the terrestrial demonstrator was done at GMV facilities. Radiation was simulated with red cards and radiation levels were determined by the intensity of the red colour assessed through a camera. The validation was successful, with the system being commanded in all 4 autonomy modes, robustly performing navigation tasks, and detecting hot spots and water spills accurately.

Figure 3: Foxizirc (left) and SherpaTT (right) during the ADE field tests (SherpaTT image courtesy DFKI)

4 AI-ENABLED AUTONOMY: CISRU

CISRU is an ESA co-funded building block project fully developed by GMV. As CISRU is an ongoing project, currently the project has reached its CDR, and we are currently under the development phase. Hence, we report hereafter the very promising preliminary results and how they contribute to autonomous decision making in complex robotic scenarios, complementing core functionalities from ERGO and ADE developments.

4.1 Objectives

CISRU aims to develop an AI-enabled software suite for complex robot-robot and robot-human applications to fuel-up the ISRU (In-situ Resources Utilisation) scenario for Moon exploration and beyond.

The first objective of this project is to carry out a study of the state-of-the-art in terms of collaborative robotics to focus on development of the SW Suite for the most critical needs.

The second objective is to define the most suitable SW architecture, based on ECSS standards, to embed the CISRU solution in other existing platforms, so that the SW suite can be integrated in multiple applications.

The Third and most important objective, is to design and implement an AI-enabled software suite based on the already existing ERGO framework, for multi-agent collaboration in robot to robot, and robot to human scenarios with enhanced planning/re-planning at multi-robot level, developing also advanced functions required for the collaborative work.

The SW architecture proposed shall be applicable to both terrestrial and space applications, and their particular constraints. Transferring space technology knowledge to terrestrial scenarios implies considering space constraints but also terrestrial requirements while designing the architecture guidelines. In this regard, most of the AI functionality is designed to be deployed on space-compatible FPGA architecture, so that it can be hosted on hardware with fewer constraints and yet be compatible in both scenarios. In addition, the components developed for this project interact with the FPGA using a module that ensures further compatibility with other space software.

4.2 CISRU Use cases

CISRU intends to show its capabilities during two different use-cases. The first use-case is based on the human and robot collaboration tasks that can be performed during extra-vehicular activity (EVA) missions, in this case, a solar panel array maintenance task. The second use-case, however, is based on the complex robot-robot exploration and resource detection collaboration tasks.

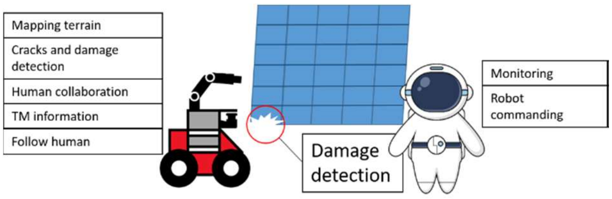

Figure 4: CISRU Use case 1

There is no ontological difference between Astronauts and Robots, both act as agents, that can command and be commanded from other agents or from Control Stations. For this use-case, we are also developing a Human-Machine Interaction console for the Astronaut's suit.

This use-case involves different autonomy robotic techniques: 1) a deep learning component to detect any damage or crack in the panels, 2) a robotic manipulator system that is used to point to the panels and point to the damage on the panel so the Astronaut can easily see where the problem is and how to solve it, 3) a machine learning component for the robot to interact with the astronaut and approach him safely; and 4) a deep learning component to supervise what the astronaut is doing.

All these techniques interact with the planner inherited from ADE and ERGO, which will allow the mutual interaction between the different agents.

Developing a system where astronauts and robots are doing a task together implies to consider not only the main technical aspects of the interaction, but also the social aspects that may affect the proper development of the task. With this paradigm in mind, we are currently developing the interaction based on safety and socially acceptable approaches between the agents (like distance with respect to the human, speed for approaching, as well as other considerations [40])

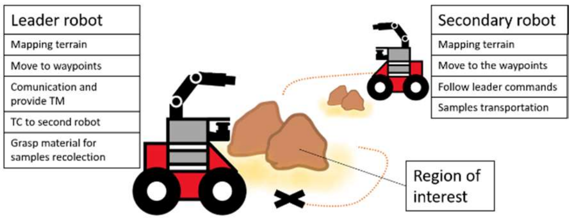

Figure 5: CISRU Use case 2

The second use-case involves two robots collaborating to map and characterise the environment. This approach will be especially useful during the exploration missions since it enables fast and reliable terrain mapping and characterisation.

One robot will act as a leader, and the other as a support, and both will be traversing along selected waypoints to recognise the environment. The leader robot will carry a scientific tool (VIS-NIR vision system) to analyse the main geological and mineralogical properties of the terrain. When the leader robot finds any interesting point, sends a message to the secondary robot, requesting its approach to the point. Both rovers will then collaborate sharing a set of tools to get soil samples that will be stored on the secondary robot. A tool-changer system is needed and has been designed to accomplish this task. In addition, a regolith/sample container will be added to the secondary robot. Once the container is full, the robot will come back to the main base to deliver the samples. Then it will return to the point it was before the receiving the message from the leader. Although the leader robot is the one who carries the tool manipulator, both robots are able to detect any interest feature on the terrain and re-plan its tasks considering this latest information. The software suite is currently in the development phase, and preliminary results have been obtained during an AI architecture trade-off. These results show how promising is to use AI-based autonomy in space exploration and we will present the results in a future issue of this paper.

5 CONCLUSIONS

Autonomy is key for present and future robotic space and terrestrial applications. In this paper we discuss our experiences with respect to autonomy in three important projects, ERGO, ADE and CISRU.

The key for autonomy is to provide systems with the capability to make decisions autonomously. To achieve this, it is necessary to combine a hierarchy of different autonomous capabilities: from mission planning/re-planning to autonomous guidance, autonomous perception and localization, autonomous manipulation as well as detection abilities (targeted to scientific characterisation or to enhance environment perception and interaction in complex tasks involving other agents). The ultimate objective is to develop robots as intelligent agents, that can collaborate and cooperate to achieve common goals.

In ERGO we developed a framework comprehensive of most of these autonomous capabilities, organizing them into a hierarchy of components. These components have been. reused and tailored for different robotic applications and tested in multiple planetary and orbital scenarios.

A key element in ERGO was the onboard mission planner/scheduler (the so-called agent), which allows to command spacecrafts based on goals (E4). The ERGO system allows to command the system not only using high-level goals, but also different levels of autonomy. Lower levels of autonomy can be applied to recover from dangerous situations meanwhile higher levels of autonomy improve operational efficiency along nominal situations.

ADE reused most of the ERGO components demonstrating its validity in both space and terrestrial scenarios. ADE also refined some of the ERGO components, and included the perception and mapping capabilities from I3DS, that were enhanced. Performance Figures of Merit for localization and perception and autonomous guidance met expectations and, in some cases, surpassed the requirements.

In ADE, the mission planner from ERGO was also improved and it provided excellent results. The combined capabilities of mission planning and scientific detector for opportunistic science are evidenced as key assets yielding an (unprecedented) level of on-board autonomy.

Our approach for RAMS is based on a separation of criticality. Additional methods for the validation of

RAMS are, besides testing, those related to model-checking, with statistical model-checking as best suited. Such an approach would allow to ensure RAMS by design at system and component level, by exploring a reasonable subset of the state space (including the actual implementation of the system) and collecting statistical evidence. This approach has been successfully used for the design of the FDIR components in ERGO and ADE, and for the validation of the system requirements.

CISRU, built on the ERGO, is a paramount example of the use of multi-agent and represents the last step for the consecution of autonomy.

The use of AI is key in achieving autonomy contributing to enhance perception (better understanding of the environment via semantic segmentation) and interaction to other agents and objects present. We are using different techniques of AI, like Automated planning for the onboard mission planner, Neural networks for scientific detectors, and Deep learning for perception and localization.

Finally, both ADE and ERGO are excellent examples of the fruitful collaboration of European space actors and demonstrated the interoperability/integration of the PERASPERA SRC Building Blocks.

CISRU, an ongoing project, exploits and extends these capabilities to the robot collaboration and cooperation arena, with additional features using AI.

All these projects are paving the way for future autonomous robots in both space missions and terrestrial applications

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