PRO-ACT: Planetary Robots Deployed For Assembly And Construction Of Future Lunar ISRU And Supporting Infrastructures

PRO-ACT: PLANETARY ROBOTS DEPLOYED FOR ASSEMBLY AND CONSTRUCTION OF FUTURE LUNAR ISRU AND SUPPORTING INFRASTRUCTURES

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ABSTRACT

The world's space agencies, including ESA have been considering various strategies, architectures and mission concepts to explore the solar system in the frame of international cooperation. There is a consensus in that the lunar vicinity is the most appropriate next step for sustainable exploration. Key principles in said exploration are affordability, exploration value, partnerships, capability evolution, human/robotic partnership and robustness. Private sector interest in lunar exploration and resource utilization is also on the rise. In-Situ Resource Utilisation (ISRU) enables sustainability in space exploration through the harnessing of resources that are available in space in order to create products and services for robotic exploration, human exploration, and for commercial purposes. PRO-ACT aims to demonstrate the capability of using autonomous robots working collaboratively to assemble an ISRU plant on the moon and supporting equipment.

1. MOTIVATIONS

ISRU creates opportunities for robotics exploration [1], human exploration [2], and for commercial purposes. Studies have been performed on the economic viability [3] of utilising the resources of space in various relevant scenarios, which include, among others, the market of LEO to GEO transport based on H2/O2 propellants, leveraging the fact that LEO is more accessible from the Moon than from the Earth's surface in terms of Delta V budget.
The fact that such propellant can be also utilised by government agencies for robotic and human Solar System exploration missions, if provided at strategic fuel depots in cis-lunar space or on the Lunar surface, creates a strong rationale for public-private partnerships aiming for commercial services sustaining lunar operations.

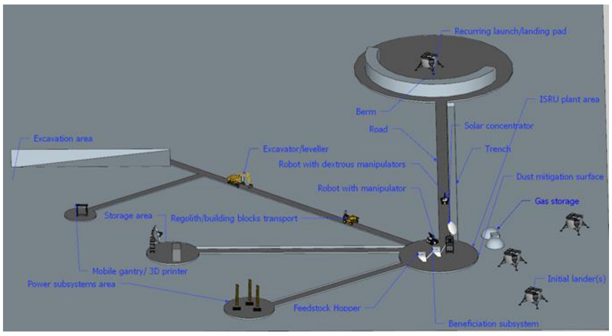

Figure 1. Lunar base concept (credit: Space Applications Services)

The installation, construction and operation of such plants will require advancement in the field of autonomous robotics (in particular if a site of high scientific interest such as the South Pole Aitken Basin on the far side is selected), as well as the use of construction technologies that have been a focus of research, namely the use of regolith for civil construction [4] (e.g. preparation of launch pad berms for lander dust mitigation, interlocking elements for construction of shelters, consolidation of the ground to produce roads), Fig. 1. Such ISRU plants, would serve as a source of water and oxygen, enabling human outposts, and for delivery of hydrogen and oxygen [5] fuel to various locations in cis-lunar space. Civil construction systems could be used to create radiation shelters for habitats delivered from Earth.

2. OBJECTIVE

Towards this objective, the PRO-ACT project aims to demonstrate a novel approach of deploying multiple robots to work towards achieving common goals by (i) cooperative goal decomposition (ii) cooperative mission planning and execution (iii) cooperative manipulation for transport and assembly of the aforementioned ISRU Pilot Plant and its supporting infrastructure that will be of strategic value for proposed future lunar unmanned and manned exploration missions [6]. Such a system will open up new opportunities for mission design, allowing advance preparation of human lunar outposts, and significant up-mass savings for future lunar missions and acting as a solid demonstrator of the feasibility to build an In-Situ Resource Utilization (ISRU) large-scale plant.

This disruptive application and integration of robotics technologies from the research domain will enable new mission design opportunities and strategically develop Europe's capacity in this area. The picture below illustrates a potential overall concept (dimensions are notional, generally not to scale) of an actual lunar base precursor mission initially centered around the Oxygen generation ISRU plant. This concept is based on studies conducted on Lunar ISRU [1] [3] by national Space Agencies and doing a possible projection of the current plans of ESA. This proposal addresses the establishment, with the support of mobile robotic platforms, of a precursor lunar base with essential capabilities in preparation of commercial exploitation of in-situ resources by assembling an ISRU plant and a mobile gantry for 3D printing building elements for future human habitation. There have been many studies such as ALCHEMIST ground demonstrators [7] developed to demonstrate the effectiveness using regolith for creating building blocks and extracting useful elements for human life support.

Specific Objective 1: The primary objective of PRO-ACT is to implement and demonstrate multi-robot collaborative planning and manipulation capabilities in a lunar construction context, relying on, extending and integrating the outcomes of OG1 (ESROCOS) [15], OG2 (ERGO) [16], OG3 (InFuse) [17], OG4 (I3DS) [18] and OG5 (SIROM) [19], with a focus on: (1) enabling assembly of an ISRU plant on the moon as precursor to human settlement and (2) partial assembly of a mobile gantry which can also be used for 3D printing building elements for assembly and construction of human habitats, and address critical concern of dust mitigation.

Specific Objective 2: Developing robust multi-robot cooperation capabilities allowing joint interventions (including navigation in close vicinity and joint manipulation actions) in mixed structured / unstructured environment. Making the capabilities available within a CREW (Cooperative Robotics for Enhanced Workforce) module, consisting of integrated components from ERGO, InFuse, cooperative SLAM and ESROCOS.

Specific Objective 3: Customizing existing mobile robotic platforms and preparing facilities (moon analogue) for performing tests and demonstrations in a selection of relevant, partially representative scenarios of moon construction activities in relation to (1) ISRU capabilities establishment and (2) preparing dust mitigation surfaces (3) assembling and deploying a gantry/3D printer.

3. SCENARIOS

In particular there are 2 important areas (i) 3D printing of relevant structures using regolith (with or without adjuvant, depending on printing strategy) for construction purpose – e.g. panels for berms, brick like elements for shelters, tiles for landing pads and roads for dust mitigation (ii) extraction of oxygen from regolith to serve as oxidizer in rocket fuel and for providing a breathable atmosphere in habitats.

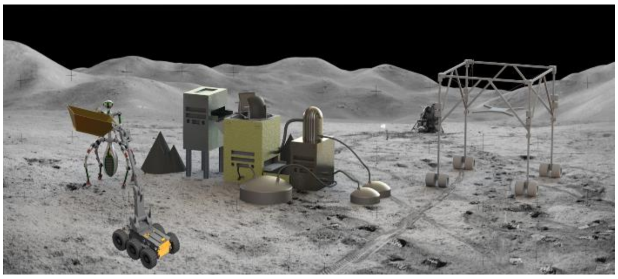

Figure 2: Concept of cooperative assembly of an ISRU plant by RWAs

The proposed concept in Fig. 2 was designed to overlap with the requirements from the SRC Guidance reference document SPACE-12-TEC-2018 [20] for multi-robot collaboration in planetary construction scenario. Some of the main objectives addressed in the scenario are as follows:

1. Fine scale surveying of areas prior to carry out construction work using cooperative mapping.
2. Site clearing by grading (from stones and debris) [8].
3. Unloading equipment/construction elements from the lander(s) and transporting them to the sites.
4. Assembly of modular components of an ISRU plant Fig. 3 and assisting the partial assembly of 3D printing cable driven gantry Fig. 4.
5. 3D printing of modular building elements from regolith and assembly of large elements (beams, pillars) to construct storage and habitation spaces.
6. Dust mitigation is a major concern for durable and safe operations. This is addressed by the tiling of surfaces, relying on 3D printed tiles. This applies in particular to paths connecting key areas.

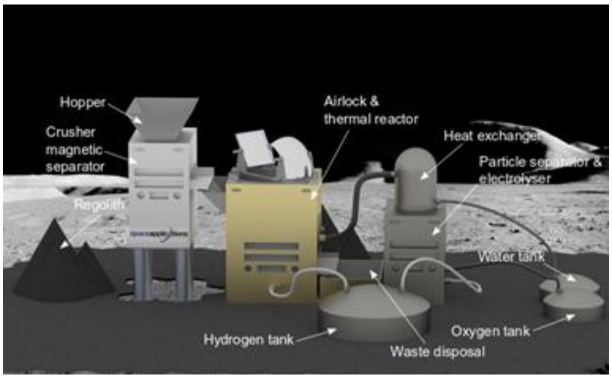

Figure 3: Concept of a modular lunar ISRU plant with sub-systems which can be assembled

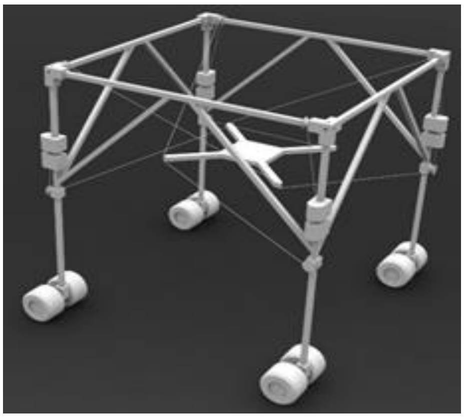

Figure 4: Concept of mobile (passive) gantry by assembling modular beams and connectors

4. SYSTEM ARCHITECTURE

The PRO-ACT core objective is to compose previous OG1-5 building blocks with minor adaptations and minimal development of complementary supporting systems where necessary for the application scenario, to enable RWAs to perform complex cooperative task planning and manipulation behaviors. To achieve this objective, the system architecture at RWA level has been simplified from the perspective of space grade computational architectures, but strongly considering the constraints that they impose in terms of processing capability, memory, real-timing and data storage.

The system architecture (Fig. 5) will be compatible with existing mature RWAs – IBIS, Mantis and Cable Gantry (it will be adapted as a mobile gantry share a similar planning, data fusion and sensing architecture:

1. RWAs are locally equipped with custom developed low level controllers (microcontrollers or ARM based) for locomotion and manipulation.
2. Robot hardware specific HAL (Hardware Abstraction Layer) or equivalent drivers are available to make these real time interfaces available to the higher-level computers.
3. Robot mission planners, perception and navigation will be deployed in regular x86 architecture Linux based systems interfaced with the HAL via custom middleware.

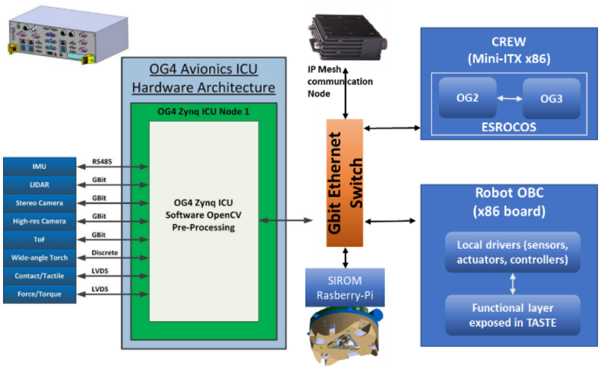

Figure 5: PRO-ACT System architecture and interfaces relevant for each RWA

In PRO-ACT, an additional computer will be foreseen for the CREW to come as an add-on autonomy module for the 3RWAs. This will be based on an x86 architecture that is interfaced with the robot's existing OBC via Gigabit Ethernet. The CREW computer will host software related to ERGO (including cooperative mission planning, cooperative manipulation planning and control) and InFuse (including cooperative SLAM) as ESROCOS software components running within the framework as the robot control operating system/middleware. The robot OBC (On Board Computer) will be adapted to include ESROCOS as a supplementary middleware to the existing one, to enable the RWA provider to expose the functional interfaces of the robot as ESROCOS interfaces. The robot OBC will also be connected to common Gigabit Ethernet local network to allow the CREW to send high level controller commands and receive low level sensor feedback from the RWA (existing perception sensors, arm and wheel encoders, current or strain gauges etc.).

1. The RWAs would additionally be equipped with a compact version of the OG4-ICU with interfaces for OG4 sensors (ToF Basler camera, Force/Torque sensor, IMU, high resolution camera and stereo camera) and existing RWA specific COTS sensors a such as stereo bench, LiDAR, tactile sensors, F/T sensors etc. The ICU itself is connected to the RWA local network via Gigabit Ethernet.
2. The SIROM interface will be commanded from the CREW computer to send commands to the end effector tools (drill, gripper) and to acquire specific low bandwidth data from tactile and force/torque sensors. Each SIROM will internally have a control board with an Ethernet interface.
3. The ip mesh based communication nodes for outdoor conditions [9][10][11] and Wi-Fi access points for indoor tests will be available on each RWA interfaced to via Ethernet to the central Gigabit Ethernet switch providing communication link to other RWAs for the CREW to communicate and exchange data related to cooperative task planning and mission execution.

Supporting details for each software and hardware components are described below with a background review, specific adaptations and supporting developments to comply with this system architecture.

4.1. RE-USE OF BUILDING BLOCKS

1. ESROCOS will be used the common RCOS (Robot Control Operating System) for wrapping most of the software components on the RWAs. Available and custom ESROCOS PUS services will be used to send mission goals and transmit telemetry to the monitoring station during testing and validation operations with RWAs.
2. ERGO will form the core of the CREW architecture for mono-robot level task planning and execution, with adaptation and extensions of the ERGO reactors for cooperative multi-agent scenarios and inter-robot task planning and execution. The existing path planning and trajectory control algorithms needed for the robot platforms will be configured with RWA

models, functions and resources (time, energy) for each use case scenario.

3. InFuse data fusion methods will be selected and deployed on RWAs for localization and mapping to support the CREW planners and controllers. It will be based on vison and/or Lidar based methods, performance and accuracy requirements, robustness to lighting conditions, types of feature detection and tracking etc. This includes the set of data fusion techniques that can be included into the cooperative SLAM framework.
4. I3DS ICU will be modified to have a compact form factor with required power and sensor data interfaces to make it compatible for mounting on RWAs. I3DS ICU developed by OG4 is provided in an industrial CPCI rack. The on-board pre-processing by partial acceleration in the FPGA will reduce the computational load on the RWA computer.
5. SIROM hardware interfaces will be used as the base connector on the end effector of the IBIS mobile manipulator robot. The base connector will interface with tools such as a gripper, shovel and drill that also have SIROM interfaces as the base connector.

4.2. CREW

The CREW (Cooperative Robotics for Enhanced Workforce) module will endow each robot with the following capabilities: (i) Autonomous navigation and path planning (existing ERGO capability) (ii) Absolute and relative spatial localization (existing InFuse capability) (iii) Cooperative decision-making and task execution (planning and control extensions) (iv) Adaptation to task re-assignment (ERGO extensions). Fig. 6 highlights the proposed architecture of the CREW with its interface to the function layer of robots, which will be deployed and integrated on RWAs. Software components within the CREW will be developed or wrapped into ESROCOS components.

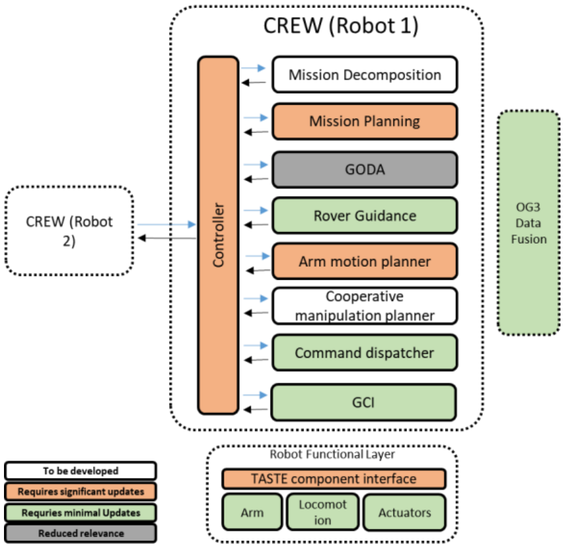

Figure 6: CREW as an ERGO agent with extensions

The ERGO mission planner will be extended to communicate with a corresponding mission planner on another RWA to synchronize tasks during execution and adapt to task re-assignment. This provides some sort of supervision of the proper execution of the coordinated plan. This entity will be in charge of harmonizing all these activities. In the specific case of cooperative manipulation, this involves a centralized closed loop synchronized planning and control of the manipulator and the mobile robot base. This requires high frequency trajectory and motion, planning and control (around 50Hz) which is coupled. Fig. 6 shows the software components within the CREW which is foreseen as an extension of ERGO with the cooperative manipulation controller in the functional layer.

Cooperative Mission Decomposition: The ambition of PRO-ACT with regards of distributed task allocation is to develop an elitism process within the distributed solver able to prevent potential allocation conflicts [12], thus allowing RWAs to achieve the most elite solution in the present generation. The auction principle will be adopted to achieve this coordination because of its efficiency and feasibility for the distributed planning framework. The solution to distributed task allocation problem will be innovatively presented in PRO-ACT as a coupled method, which solves two coupled sub-problems: task assignment and trajectory generation (the module below based on OG2 development). Therefore, the trajectory generation algorithm adopted in the CREW module is used as a subroutine in the task assignment algorithm and developed as constraints for the task allocation formulated as MILP optimisation problem.

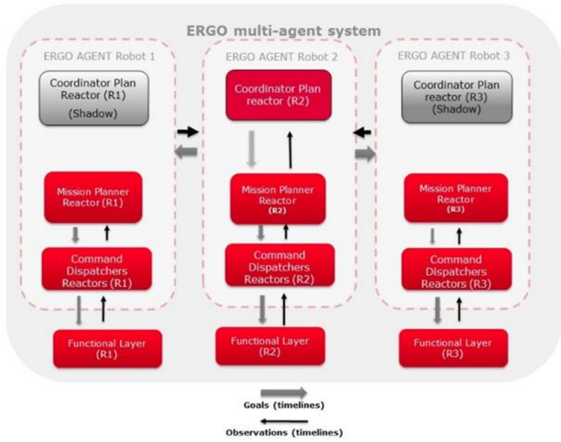

Figure 7: ERGO multi-agent architecture

Multi-agent mission planning: The literature on agents usually divides the agents into two categories: deliberative agents and reactive agents. Deliberative architecture is a particular type of knowledge-based system and is defined to be one that contains an explicitly represented symbolic model of the world. Deliberation is the explicit consideration of alternative courses of actions; generating alternatives and choosing one of the possible alternatives. Decisions are made via logical reasoning based on pattern matching and symbolic manipulation. In contrast, reactive architectures are based on pre-defined behaviours. In rapidly changing environment, such as the real world, where the agent must react quickly to external changes, there may not be time available to perform many time-consuming actions such as planning and introspection. The extended ERGO multi-agent mission planner instance (Fig. 7) will be a coordinated planning reactor, but that will consider in its plan exclusively the high-level goals to be performed by each robot, with the associated time. It will handle the plan for the collaboration of the different robots, and be responsible for their coordination, considering only high-level goals, without having to deal with the low-level actions of each individual robot.

Collaborative manipulation for transportation and assembly: The ambition of PRO-ACT is to further investigate the robust implementation of such dual-arm robot manipulation planning and control algorithms based on the frontline techniques recently developed in these fields. Robust synchronous/cooperative control strategies, enabling a dual-arm robot system to manipulate objects firmly with both hands, as well as specific dual-arm closed kinematics planners will be implemented for the generation of collision-free joint trajectories satisfying a set of Cartesian task-space constraints. The challenge also comes from the need to coordinate the arms and the mobile platforms motions of the RWAs involved in the coordinated transportation task, such as the Mantis robot with two 7 DOF manipulator arms and the IBIS mobile manipulator equipped with a 6 DOF robot arm. Reliability and adaptability to a diverse panorama of operative conditions and imprecise knowledge of all the system parameters, especially for what concerns the environment (e.g., terrain) and the load to be manipulated (e.g., grasping points) will be major points of investigation for the conception of the control of the cooperative manipulation.

4.3. Cooperative SLAM and sensor fusion

A selection of the planetary DFPCs (Data Fusion Processing Compounds) from InFuse (OG3) will be re-used and adapted in a few cases for the target scenarios. Some of the main DFPCs applicable to the scenario to be re-used are mentioned below: (i) Visual Odometry - Based around a stereo camera, provides an estimate of the pose of the rover by computing its displacement between two consecutive frames, without any memory of the frames on a longer horizon (ii) Visual SLAM – creates and maintains a long-term map of the explored terrain, which promises to improve localisation accuracy, especially if an area is revisited and a loop closure can be computed (iii) Point cloud based localization - to perform a robust tracking of a known target described by a point cloud, either obtained through LiDAR sensors, stereo cameras or ToF cameras (iv) Absolute localization - provides a pose estimate of the rover, using a DEM built with orbital data, and taking as inputs the LiDAR point cloud or point cloud provided by the stereo images and a pose estimate (v) DEM generation – builds a Digital Elevation Map (DEM) from point clouds provided by LIDAR or stereoscopic imaging sensors (vi) Pose fusion – pose estimation by fusing multiple pose estimates from other DFPCs to improve accuracy (vii) Lidar SLAM - Simultaneously builds an environment model composed of a series of LIDAR point clouds and provides pose estimates for the rover (viii) 3D Model detection and tracking - Supports detection and tracking of known rigid deformable objects. This DFPC is intended to be used on close range applications.

Additional DFPCs would be composed from the DFNs and integrated with the RWAs for specific tasks: (i) Visual servoing - Image based data fusion methods to identify and track features (2D or 3D), markers or lines at a high frequency as a precursor for manipulation. The feature position estimator needs to be coupled with robust and efficient motion planning of the robot arm and end effector when getting close to the target (ii) Co-registration and moving target suppression – to support of cooperative SLAM. It collects 3D point clouds (un-scaled and then scaled) generated by each RWA for motion estimation and generates the transformation between the reference systems of the RWAs by using the approach of registration problem. The registration yields enhanced accuracy in localization of one RWA relative to the other. The transformation stemming from the registration enables a cooperative stereo setup and thus an improved absolute 3D positioning of common feature points in the scene. Additionally, targets in motion can affect the correct registration.

4.4. Robotic Working Agents (RWAs)

Figure 8: IBIS Mobile manipulation robot

Mobile manipulator – IBIS is a robot designed for pyrotechnic operations and reconnaissance. This platform has a six-wheeled chassis with independent drive of each wheel allows to operate in challenging and varied terrain. IBIS (Fig. 8) was designed for fast motion (10 km/h) with off-road capability. Special design of mobile base suspension ensures optimum wheel contact with the ground. Manipulator with extendable arm ensures a large reach (over 3m) and a high range of motion in each plane. Device is currently teleoperated with limited autonomy, which will be modified to host multi-robot autonomy functions. For the current project, following hardware and platform drivers modifications are planned: (i) Addition of two SIROM interfaces on the end of manipulator (one for end effectors, one for sensors) (ii) addition of full set of sensors required for collaborative RWAs actions (Force/torque on the end of manipulator, and tactile sensors for gripper) (iii) integration of gripper (with minor mass adaptations) with SIROM at the base (iv) low level S/W drivers modification required for platform integration with ESROCOS (v) integration of position control SW for manipulator (vi) preparation of interfaces for ICU – power, data interfaces, cabling, mounting (vii) selection and integration of additional LIDAR and stereo camera (viii) selection two COTS end-effectors: adapted drill and shovel, integration with SIROM.

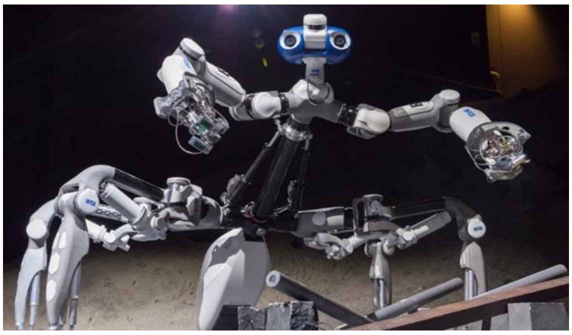

Figure 9: Mantis in four-legged manipulation posture

MANTIS is a multi-legged robot with six extremities as seen in Fig. 9. With a height of more than 1,7 m (when erect), the robot weights 110kg. The system was developed as a platform for interdisciplinary research in the area of mobile manipulation with multi-legged robots. To fulfil a variety of different tasks, the robot is capable to operate in two different modes:

- In the locomotion modus, the robot walks on all six extremities. This is a big advantage in difficult terrain and contributes to the excellent all-terrain capabilities of Mantis.
- In the manipulation mode, Mantis uses the four rear legs for locomotion and the two front legs for manipulation. This enables Mantis to use dual-arm manipulation while being firmly grounded.

The flexibility of Mantis enables the robot to solve complex scenarios and manipulation tasks with only one system. Mantis has 61 actively controlled degrees of freedom. Two arms with 7 degrees of freedom each, as well as a three-fingered gripper equipped with pressure and force-torque sensors, allow complex manipulation tasks. The reactive behaviour-based locomotion control architecture uses proprioceptive sensor data from force-torque and electric current sensors, as well as from IMUs. In addition, Mantis uses a stereo camera system as well as a laser scanner for generating three-dimensional point clouds. Within the project, additional hardware and software modifications are planned. OG4 need to be integrated like a high precision IMU, a high resolution 3D laser scanner or time of flight cameras. To process the sensor data and fuse another CPU needs to be integrated for the CREW multi-robot task and motion planner (built around ERGO OG2) embedded in ESROCOS (OG1). For dexterous and flexible manipulation tasks, the existing 3 finger grippers on the 2 arms are quite complex and capable. Software adaptations are also planned to realize a safe and reliable robot control which utilized the new as well as the existing sensor and actuator modalities. The low-level control of Mantis will remain with the native operating system (ROCK). Thus, a suitable interface between ROCK and ESROCOS will be developed.

Figure 10: Pylos extruder (left) and Cogiro (right)

The fixed gantry setup was initially developed as a combination of Tecnalia Cogiro and IAAC Pylos projects [13][14]: Pylos (Fig. 10) is the result of a research action at IAAC on large scale Additive Manufacturing -AM -processes, for architecture. Cogiro is a suspended CDPR owned by Tecnalia and CNRS-LIRMM. Its original point of design resides in the way the cables are connected to the frame, which makes it a very stable design. It is capable of holding a load up to 500kg over more than 80% of the footprint. Advances in robot control have allowed to reach repeatability in the millimeter range and precision in the low centimeter range. Adaptations for the project include escalation of the system, design of a dedicated subsystem for storage and deployment and adaptation of the 3D printer for the validation of the developed technology in partially representative environment. The mobile cable gantry is transported on the lunar lander in stowed configuration. After landing and site preparation, robots in collaboration will bring it to its operating location. While laid in the ground in horizontal position, (Fig. 11), both robots will lift the stowed gantry and place it in vertical position. While the IBIS robot maintain one of the struts fixed on the ground, the RWA will pull sequentially the other 3 struts until complete deployment.

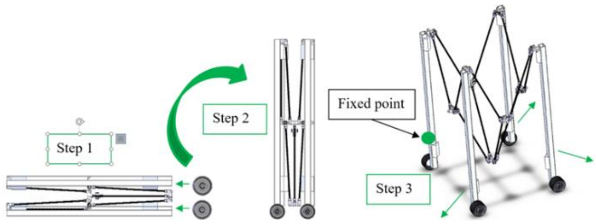

Figure 11: Concept of the modular mobile gantry solution for lifting, positioning and 3D printing; details of the freewheeling pulley and cable drawing point

4.5. Sensor Processing Unit and Common Interface

The I3DS sensor management ICU developed is provided in an industrial CPCI rack with overall dimensions that is currently too large for mounting on to the PRO-ACT planetary robots. The ICU will be adapted to a smaller form factor more suitable for a mobile planetary robot application as shown in Fig. 12(i).

SIROM is a standard hardware interface to be used for connecting (i) APMs (Active Payload Modules) – sensors, power source or connecting blocks (ii) end effector to the robotic arm, and even (iii) generic standardised mechanical, thermal and data interface. SIROM shall be mounted on the robotic arm of the IBIS robot, which will provide multi-tool capability. The three chosen tools IBIS robot can choose from are gripper and shovel, Fig. 12(ii)(iii). Gripper shall be used for transport, manipulation and construction, while the drill and the shovel shall be used for construction or conversion works. SIROM shall also be attached to gantry end effector. The idea is to then connect the gripper tool to the gantry end effector, using SIROM, giving the gantry extended manipulation capabilities and versatility

Figure 12: (i) Compact sensor ICU (ii) (ii) SIROM with gripper and shovel

4.6. Simulation, Communications & Control Center

The MARS simulator is a tool that allows full access to all sensors and actuators, and which provides already all ROCK [21] interfaces. The MARS simulator is a cross-platform simulation and visualisation tool created for robotics research. It consists of a core framework containing all main simulation components, a GUI (based on Qt), 3D visualization (using OSG) and a physics engine (based on ODE. A physical simulation environment is needed to test the cooperative planning strategies in the CREW, control laws for cooperative manipulation for RWAs and simulated sensor data before deploying actually the setup on the RWAs. Most of the software modules will be developed or adapted as ESROCOS components. To integrate and test the functionalities w.r.t navigation, locomotion or manipulation tasks, ESROCOS interfaces shall be provided for the simulated agents within the simulator. A Mantis model is already available with all existing sensors and actuators (Fig. 13). Thus, it can be controlled as in the real configuration. The simulator will also include the model of the adapted IBIS mobile manipulator robot, to enable both the RWAs to be tested with the CREW envelope of planning and task execution monitoring.

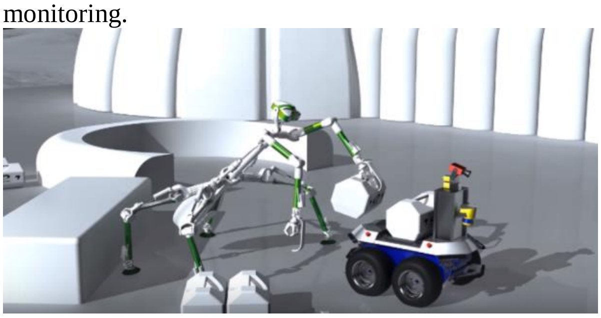

Figure 13: MARS simulator with Mantis

A wireless communication system using a combination of mature, field-deployed data link technologies operating in unlicensed spectrum as well as commercial software defined radio services, will be implemented to provide and unified, transparent connectivity service to all 3 RWAs and the SMC. The use of ip mesh cognitive radio [9][10][11] shown in Fig. 14 with intelligence, dynamic channel/power/rate control, broadcasting, multicasting and multi-hop mesh-networking will be exploited to guarantee the overall required range (0.2 – 0.5km), throughput (up to 20-25 Mbps) and reliability with minimal interference from coexistent external networks. A backup Wi-Fi link will be available for testing in lab (indoor) and short-range conditions.

Figure 14: Mobile Ad Hoc Networking (MANET)

A Supervisory Monitoring Center (SMC) will be used only for high-level global mission planning and monitoring the mission planning schedules, progress of the multiple RWAs missions during operations. The command and monitoring base station will be deployed near the analogue, capable of planning high level missions for robots to execute their tasks cooperatively. The SMC (Fig. 15) will be equipped with a local GIS containing offline 2D or 3D earth and planetary (or analogue) base maps from sources such as ESA, NASA, Google, analogue DEMs etc. that will be rendered in the interactive map interface. The backend of SMC has a ROS interface. The EROCOS-ROS bridge **Error! Reference source not found.** will be leveraged to RWAs and EST (simulator). The absolute pose of the RWAs will be updated dynamically as a layer on the orbital or satellite map interface and the local pose of the robot will be rendered in the local DEM that is constructed by the robot, along with a 3D model of the robot. Existing (ESROCOS) and custom PUS services will used to acquire RWAs telemetry, sending mission goals, monitor and log runtime status for reviewing failures.

Figure 15: Robot Command and Control Station software with multiple ground

5. VALIDATION IN LUNAR ANALOGS

ESA's Planetary Robotics Laboratory tested its Heavy Duty Planetary Rover (HDPR) as part of ESA's Lunar Scenario Concept Validation and Demonstration (Lucid) project in the Teide National Park in Las Minas de San José (Fig. 16 bottom right). Other potential sites include the Lanzarote (Fig. 16 top) or La Palma (Fig. 16 bottom left). The actual sites that have a proven track-record for earth analogue studies by ESA and NASA:

- Lanzarote: Timanfaya Park, Charco de los Clicos, Cueva volcánica del volcán de La Corona
- Tenerife: Teide National Park, Cañadas del Teide, Macizo de Anaga.

These sites represent a wide range of morphological conditions, which means that the most suitable site will be selected, once the PRO-ACT demonstration mission parameters are finalised.

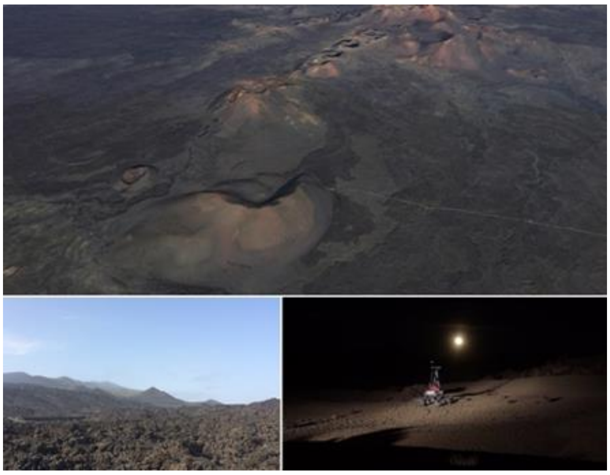

Figure 16: Potential outdoor analogs in Canry Islands

The new ESA LUNA analogue in Fig. 17 is the main indoor lunar analog for testing and validation. It will be unique and different in capabilities and utilization concept – it is free for usage and an open platform concept for any European research groups interested and working in space applications.

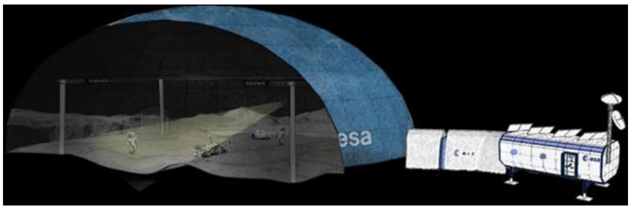

Figure 17: EAC-LUNA indoor lunar analogue

6. CONCLUSION

PRO-ACT aims to comprehensively implement and demonstrate multi-robot collaborative planning and manipulation capabilities in a lunar construction context. The heterogeneous team of robots with different capabilities require the development and integration of advanced mission planning, motion control and perception capabilities to achieve the operational scenarios. The re-use of robotics building blocks is a step towards composing complex unmanned systems from core robotics software frameworks. Technologies developed for this long-term future application of multiple agents have terrestrial applications in areas such as construction, mining, and manufacturing.

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