MULTI-ROBOT COOPERATION FOR LUNAR BASE ASSEMBLY AND CONSTRUCTION

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ABSTRACT

The PRO-ACT project aims to develop key technologies for multiple robots to work cooperatively for future lunar assembly and construction tasks. This paper provides an overview of the underlying software and hardware technologies re-used from related space robotics technologies, new developments and specific adaptations for addressing project specific requirements.

1 INTRODUCTION

In-Situ Resource Utilization (ISRU) on the Moon to support future exploration outposts and for commercial purposes is one of the main goals of planetary exploration research. With the increase in planned robotised prospecting missions, both by space agencies and commercial ventures, and the advent of AI in space, cooperating robots will augment the capability to achieve goals collectively and efficiently. This is one of the main goals of PRO-ACT (Planetary RObots deployed for Assembly and Construction Tasks) [1].

PRO-ACT is part of the European Commission's H2020 strategic research cluster (SRC) in space robotics technologies managed by PERASPERA [2]. To demonstrate these capabilities, the following robots are being used: the Veles - a six-wheeled rover, Mantis - a six-legged walking system and a mobile gantry.

1.1 Scenarios

PRO-ACT aims to demonstrate the capability of using heterogeneous autonomous robots (Figure 1) working cooperatively to plan tasks, collaboratively explore an unknown area, cooperatively unload, transport large components and assemble an ISRU plant on the moon.

PRO-ACT highlights the logical and physical cooperation between several robots. The main focus is on 1) multi-robot system architecture 2) task allocation by mutual negotiation 3) cooperative task execution 4) single and multi-agent perception, mapping and localisation 5) cooperative manipulation planning and control 6) robot hardware adaptations.

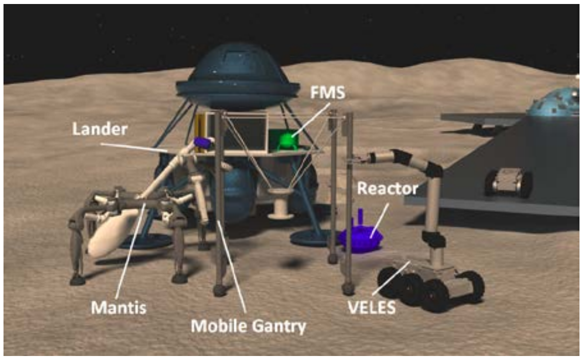

Figure 1: VELES and Mantis deploy the mobile gantry in front of the lander (animation)

2 ROBOTIC SYSTEMS

2.1 Mantis

The Mantis (Figure 2) was developed with the aim to provide high mobility and manipulation capabilities in uneven and unstructured terrain [9]. 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 two pronged hands for dual arm manipulation and a bracket to walk on. 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 dimensions of Mantis are 2.96m×1.84m×0.32m (locomotion posture) with a mass of 107 kg.

Figure 2: Mantis in manipulation pose during outdoor testing (credit: DFKI GmbH, A. Popp)

During the PRO-ACT project Mantis was adapted and improved on the hardware and software side [10]. On hardware Mantis got two new onboard computers (OBCs), an IMU and a further developed sensor-ICU (Instrument Control Unit) as an improvement of the I3DS [6]. Furthermore, the grippers have been redesigned to cover the needs of the project. The old three fingered gripper could hold 0.5 kg, the new gripper has the capability to hold up to 10 kg. On the software side the locomotion was extended. Mantis is able to walk in six-legged, five-legged and four-legged position. The five-legged locomotion mode allows Mantis to walk on its four legs and one forearm whereas the second forearm with gripper can carry a load or can be used for cooperative transportation. Mantis is extended by a Robot Client API which is independent and based on the open source robot_remote_library[13], which is under current development at DFKI. The communication layer is based on ZeroMQ and de-/serialization is handled with Google's protocol buffers (proto3). The core library was written in a way that facilitates extensibility through inheritance [8].

2.2 Veles

Veles is a rough off-road capable mobile platform with high towing capabilities and the ability to carry a heavy payload (Figure 3). Veles is a significantly modified IBIS platform tailored to the requirements of the PRO-ACT project. Modifications to the Veles platform, in comparison with IBIS include in-depth modifications of the communication suite and Monitoring and Control station (MCS), modifications to the robotic arm, changes to the gearing and packaging, and major changes of the safety systems of the platform.

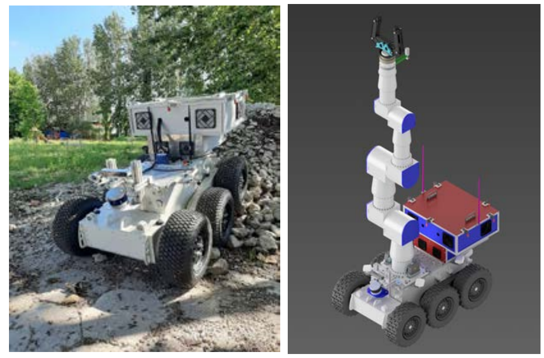

Figure 3: Veles during outdoor testing and CAD model with robotic arm

Veles can be divided into following parts: the 6 wheeled platform, the Electronics Box (EBOX) with all computers, batteries and communication hardware, the 7 DoF robotic arm with 20 kg maximum payload and sensor suite consisting of Lidar, stereo camera, IMU, wrist camera and Force/Torque sensor.

Total mass of the robot with the robotic arm, batteries and the EBOX is around 370 kg. Maximum speed is rated at 5 km/h and towing capacity rated at 200kg on wheels. Following accessories are also developed for the Veles robot for needs of PRO-ACT: a gripper that would be used during the deployment of the gantry and a grader blade that would be used for surface modifications of the simulated ISRU facility and the shovel for simulated regolith manipulation.

2.3 Mobile Gantry

The Mobile Gantry is developed for PRO-ACT with the aim of providing a flexible, high load manipulation and large work volume robotic system. The Mobile Gantry is a cable robot having two well differentiated systems, the deployable structure and the end-effector cable system itself.

The deployable structure (Figure 4) is a newly developed mechanism that provides support for the cable actuators and adds stowing and deploying capacities to the system. The end-effector cable system has industrial heritage and has been scaled in order to meet the required dimensions. The system has self-deploying capabilities by using wheel actuation and additional actuated cable that has been added to the structure. Mantis and VELES will also provide auxiliary deployment force in order to be able to achieve deployment in lunar regolith simulant

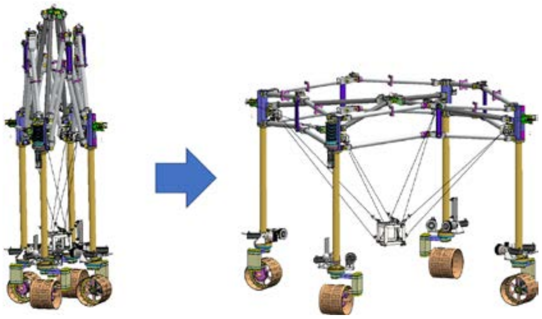

Figure 4: Mobile Gantry Deployment

terrain conditions. When deployed it has a work envelope of 1700 x 1700 x 1700 mm with a total mass of 230 kg and a lifting capacity of 500 N. The mobile platform can be fitted with different end-effectors such as 3D printer or a gripper for payload manipulation and it has all 6 DOFs within the work envelope. The actuated wheels [11] on the Gantry provide it with mobility capacities. In this context, the steering of the wheels will be performed manually for system simplicity but actuators could be added to provide autonomous mobility. The control hardware is composed of two industrial PLC controllers which will be separate units from the Gantry itself with power and communication connections to it. From a software perspective deployment control algorithms have been implemented. During deployment, all systems (wheels, deployment cable, end-effector cables, Mantis and Veles) must be actuated simultaneously in order for the deployment to take place.

3 MULTI-ROBOT SYSTEM DESIGN

3.1 Overall System Design

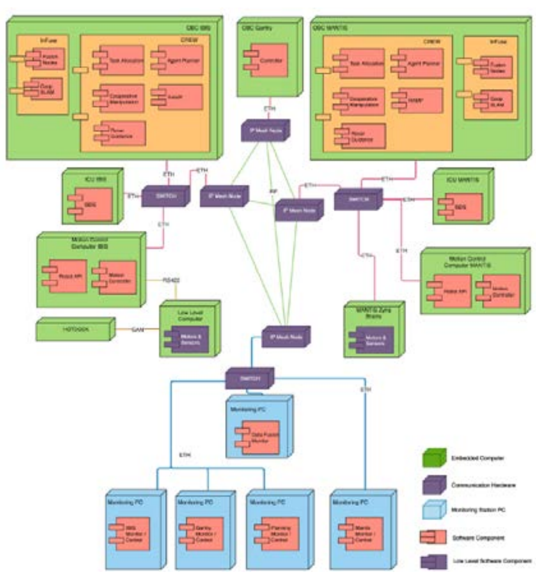

Figure 5: Deployment of the sub components

From a deployment perspective, on-board systems need processing power and communication facilities to support the interaction between software components. There are two levels of distribution of processing power - one between robotic platforms and one within each of the platforms. In figure 5, the deployment view of the sub-components are shown.

3.2 CREW

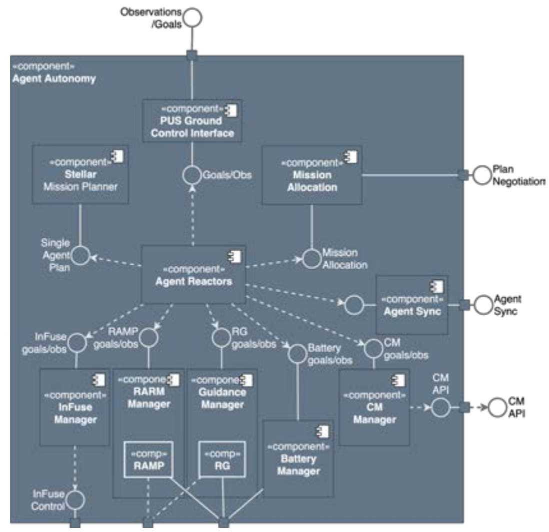

Figure 6: Agent Autonomy Component Diagram

CREW (Cooperative Robotics for Enhanced Workforce) is the result of the design process based on the reuse and adaptations of the previous building blocks (OG1-OG5) extended with new functionalities focused in maximizing the collaboration and cooperation activities for a multi-robot system. Figure 6 shows an integrated overview of the CREW Agent Autonomy component design. It represents the major software components and interfaces deployed on each RWA of the PRO-ACT multi-robot system. This section has been split in following three subsections focused in the cooperation design drive required by all multi-agent robot system:

- Cooperative Mission Task Allocation
- Cooperative Mission Planning Execution
- Cooperative Manipulation and Transport

3.2.1 Cooperative Multi-Robot Mission Task Allocation

The task allocation algorithm is a decision-making algorithm for decentralized task distribution between agents that can perform a task cooperatively. Advantages over a centralised one, especially, flexibility and task scalability while dealing with dynamic environments. However, the potential excess of communications between each agent unit represents the big challenge of using a fully decentralised approach as this can increase the power consumption to manage the communication between the agents which leads to the loss of the information. To tackle this task allocation problem in the Pro-Act Project, new optimisation techniques have been explored and used based on integer or mixed-integer linear programming (ILP or MILP). This latter is NP-hard in the way it is formulated for distributed task allocation to avoid the Inter-RWA path conflicts (between different agents) and Intra-RWA path conflicts (same agent). Based on distributed techniques, the optimal or near-optimal solutions have been investigated for such multi-robot goal assignment and present the best solution for task allocation issues also to reach real-time computation. The Share of the mission parameters between the Pro-Act platform agents while resolving conflicts in task allocations permitted to manage and produce an efficient decentralised task decision-making process among cooperative agents.

The Ground Control Interface (GCI) selects a mission, which is then passed to the Auctioneer agent as an AgenGoal function [3]. After receiving the AgentGoal function, each agent evaluates the mission tasks based on its: skills, availability, capability, and suitability to contribute to the auctioned Mission Primitive. At the end of the task allocation process, the auctioneer evaluates bids and declares the winner of the bid (auction) and attributes it to the identified robot or set of robots. The optimal plan is shared with the mission coordinator to start planning the task, seen in Figure 7.

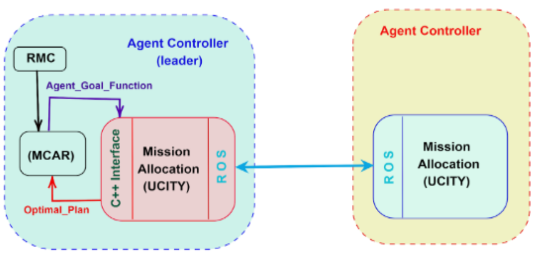

Figure 7: Task allocation with mission coordinator

3.2.2 Cooperative Multi-Robot Mission Planning Execution

This subsystem deals with the autonomous multi robots planning, coordination and execution of high-level goals using the available resources of the fleet (robots and instruments) in an optimal way. Design of the Cooperative Multi-Robot Planning and Execution component is based on the OG2/ERGO Agent concept, which at the same time, is based on the T-REX paradigm [4] [12]. An overview of the CREW architectural design (showing only two robot instances) is depicted in the following figure 8.

Each CREW Multi-Agent instance is composed by the following two main components:

1. Agent Controller and Reactors; responsible of managing and handling of the topics below:

1.1. Interactions with ground (TC & TM) using PUS services.

1.2. Interactions with cooperative multi-robot task allocation.

1.3. Multi-Robot Mission Coordination and Synchronization, including the handling of exchanged messages between different agent instances.

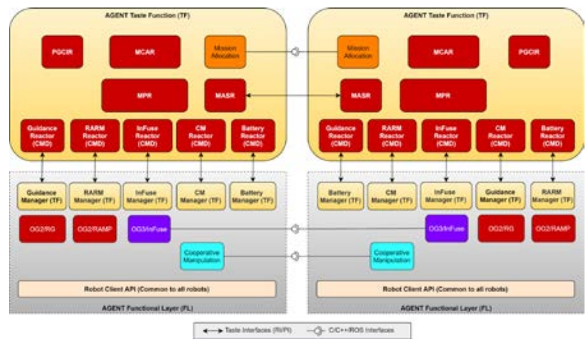

Figure 8: Overview of CREW multi-Agent Design (example showing only two CREW instances)

1.4. Cooperative Mission Planning, Monitoring and Execution based on T-REX paradigm.

1.4.1. Design and definition of deliberative and reactive reactors.

1.4.2. Definition of timelines and predicates for controlling different topics as for example; global and logical mission planning, logical path planning, arm trajectories, etc.

1.4.3. Definition of the PDDL domain and problems files in line with timelines and predicates defined based on functionalities and features statuses and the final demonstration scenarios selected.

2. Agent Functional Layer; it is the executive layer of a CREW agent instance, that is the part of the autonomous Agent implementing the commanding generated and sent (requests) from the Agent Controller to the low level robot control drivers.

Multi robots/agents systems need a high level of coordination and communications at very low rates (close to realtime). Agent's controller and reactors are responsible for the Cooperative multi-Agent mission planning, execution and monitoring of the actions to be developed by each robot in an autonomous way. For this purpose, each relevant "functionality", from the logical mission plan point of view, is modelled as a timeline that embeds a state machine representing all the statuses in which this functionality can be. This also manages coordination, synchronisation and fault recovery features based on wireless (RF) communications for reacting to unexpected events or problems during the mission execution.

3.2.3 Cooperative Multi-Robot Manipulation

Cooperative manipulation (CM) consists in having the two robots Mantis and Veles jointly using their arm to transport and/or manipulate large objects, thus achieving a task no single robot can achieve. A CM task always encompass three different phases:

1. CM mission definition: specifies the object to manipulate, the picking configurations, and the place at which it must be set. Within the whole PRO-ACT system, this phase is a result of cooperative mission planning. It could also be defined by a remote operator.
2. CM mission planning (CM2P): on the basis of the mission definition, the CM2P produces the trajectories that the robots must follow to achieve the mission. The trajectory defines the motion of the robots base and arm. This phase is a non real-time that may take up to several minutes.
3. CM mission control (CM2C): CM2C ensures the proper execution of the planned trajectories, by sending control inputs to both the base and arm of the robots. A high rate real-time controller runs on each robot, the controllers being coordinated implicitly through forces exchanges, and by exchanging status reports at a low frequency.

The execution of motion control is performed with an admittance controller in CM2C. The admittance controllers regulate position or velocity based on the force errors , using a relation describing the impedance of the mechanism (e.g. springs and dampers). For coordination between the controllers of the robots, they interact with each other passing status messages, e.g. . to synchronize the start of the motion controllers, and to monitor the motion execution.

3.3 InFuse

Adaptations and extensions were required to the InFuse framework [5] to improve the different algorithms for the PRO-ACT context and integrate it with the rest of the software.

Object detection and tracking from infuse will be used in the context to detect the lander in the scene (Figure 9 - i). The relative pose will be passed to the CREW in order to guide the two robots towards the lander. The object detection and tracking algorithms will be combined using a new algorithm in order to obtain a consistent object pose throughout the scenarios.

There are two types of algorithms that allow to obtain the self-localisation of each robot: Visual SLAM and Visual Odometry algorithms. The selected VSLAM algorithm is the Visual SLAM (with the option of using a map-based approach). The selected VO algorithm is the ros viso2 implementation. Both algorithms were tested using datasets gathered from InFuse, obtaining good preliminary performances. The DEM building algorithm will be used as well to create the elevation map of the Lunar Hall for the robots to navigate through the terrain (Figure 9 - ii).

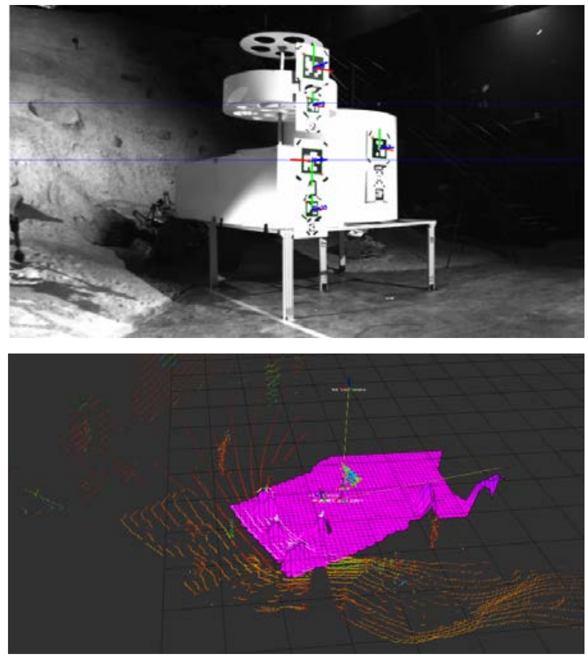

Figure 9: (i)ISRU mock-up detected by Aruco markers (ii) DEM of the terrain

The output of the data fusion performed in InFuse has to be made available to the robot path planners. Two major types of outputs that infuse produces are pose and maps.

Collaborative Simultaneous Localisation And Mapping (CSLAM) is a special type of data fusion algorithm that uses the inputs from multiple agents to perform the localization and mapping. Two main blocks are triggered concurrently on each robot, including Visual Odometry (VO) and Loop Closure Detection (LCD) algorithms. The former obtains the pose of the robot using a robust motion estimation algorithm. The latter compares the current view of the robot obtained from the stereo camera with the saved key-images on its database to detect the loop closures. The loop closure can be either intra-loop closure when the robot detects a loop from its previously observed area or inter-loop closure when the robot detects a loop from the shared images from the other robots.

The proposed CSLAM uses ROS messages to send and receive the images from the database/agents. The CSLAM publishes the 3D pose and key-images and updates the map which can be used by other agents or even other purposes like cooperative manipulation. The LCD is based on binary descriptors to retrieve previously seen similar images. The shared key-images are used to exchange between RWAs instead of Maps for VO. The local DEMs are being registered to the outcome of pose estimates obtained from cooperative VO to build the map of the environment. To validate the proposed approach, the planetary analogue real dataset of InFuse is chosen (the Erfoud dataset, Minnie in Merzouga, trajectory 22, replay 1).

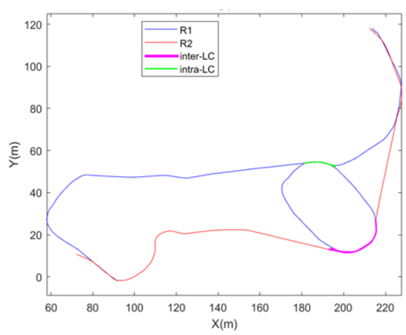

Figure 10: Detected loop closures and ground truth

The detected loop closures along with the GT of the mentioned dataset is in Figure 10.

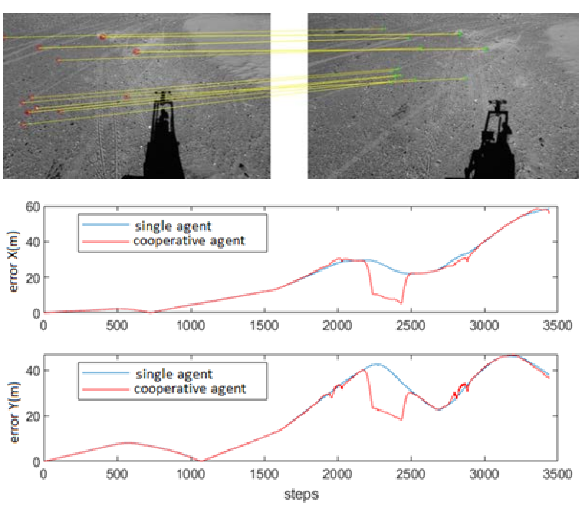

Figure 11: (i) Corresponded images and matched feature points using the LCD algorithm (ii) Comparison of estimation error for Robot 2

One of the detected loop closures and the corresponded matched images using the LCD algorithm is shown in the Figures 11(i). Also, the error of the estimated trajectory by a single and cooperative system is illustrated in Figure 11(ii). The accuracy of localisation is improved in steps near 2200 and 2500 which the Robot 2 has detected in a previously seen area by Robot 1.

3.4 I3DS

I3DS (Integrated 3D Sensors) is a combination of embedded processing hardware, a modular suite of sensors and a software framework which provides a standard interface to these sensors [6].

The key components of I3DS for PRO-ACT are the ICU (Instrument Control Unit) and the I3DS software framework. The ICU is an embedded platform based on a Xilinx Zynq UltraScale+ SoC (System on Chip). This combines 4 ARM application processors, 2 ARM real-time processors and a large FPGA fabric on a single silicon device, interconnected by high speed AMBA buses. The FPGA fabric allows the ICU to support any number of different interfaces and can provide hardware acceleration for parallel algorithms. The ICU hardware is designed with a route to flight based on European FPGA technology (NanoXplore NG-Ultra), for which the ICU is an excellent analog.

The I3DS software framework is designed to support a modular suite of sensors which can be tailored to a project's requirements and expanded to include new sensors. The PRO-ACT sensors implemented within I3DS are shown in Figure 12. The core of the framework defines a number of ASN.1 types on which all communications between sensor nodes and subscribing clients are based. An I3DS ICU is mounted on both Veles and Mantis, exposing sensor nodes on each platform which publish sensor data to subscribers. Communication with "nodes" in the I3DS network is based on zmq, a fast, asynchronous messaging library that uses a sockets interface.

PRO-ACT uses a mixture of existing I3DS sensors and new additions to the suite. The Wrist Camera, F/T Sensors and IMU are standard I3DS sensors, while the Stereo Cameras are two new additions to the suite. The Mantis stereo cameras are implemented using individual GigE Vision cameras. Veles stereo camera is implemented with a COTS USB3.0 stereo camera. An image processing node is implemented using an HLS workflow, taking advantage of Xilinx's accelerated vision libraries to offload the computationally intensive task to specialised FPGA logic.

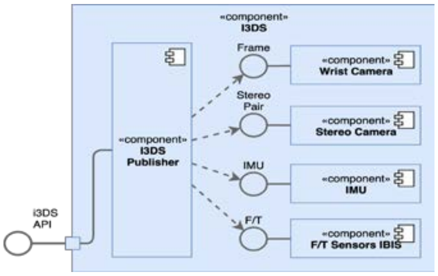

Figure 12: High-level view of the I3DS components

3.5 HOTDOCK Standard Interface

HOTDOCK is a standard interface (SI) with mechanical and electrical connectors [7]. Once it is integrated on one robotic system or module it is possible to connect the different systems and subsystems with each other also to ensure electrical and data transfer between the connected systems. In PRO-ACT the SI will be integrated for example on the mobile gantry and on the end effector of the manipulator arm of VELES. Thus it is possible, that VELES can be connected with the mobile gantry in order to to pull it.

The VELES Control unit provides two CAN interfaces, one for controlling and monitoring HOTDOCK (SI CAN Control) and the second one for communication with the Gripper/tool. Once the active HOTDOCK on the end-effector is connected to the Passive one on the gripper, the Arm Control Unit is then able to communicate with the Gripper controller by CAN. In the case of the connection of the HOTDOCK end-effector to a mechanical device, only the SI CAN control and power lines are used to operate and power the Active HOTDOCK.

The HOTDOCK controller is interfaced on one side (back connection) with the HOTDOCK control (CAN) /power lines and the power/data transfer lines. On the other side, it interfaces the connector plate (front connection). The PCB controller is also equipped with an external interface to support update of the firmware and debugging during testing.

4 SIMULATION AND EXPERIMENTS

4.1 Simulation

The analysis of the involved robotic systems and the (further) developed software in PRO-ACT is performed in a simulation area. The planned mission scenarios and functional tests of the sub components can be carried out in order to gain results of the real systems as well as to check the function of the developed software on the involved robotic systems.

Figure 13: Moon environment with Mantis and VELES in the MARS simulator

MARS is chosen as the environment simulation tool. It is based on the rock framework (www.rock-robotics.org) and used to simulate the physical state as well as the visual representation of the robots (Figure 13). The rock framework allows to represent an entire robot with all joints, sensors and actuators fully defined and functional allowing to operate the real system or the simulation.

4.2 Remote & Intermediate Tests

Multiple integration and intermediate tests with Mantis, VELES and the lander mock up were carried out in the space exploration hall in Bremen [14]. Main goal was the integration of the software developed in the project and first functional tests of the robot systems with the implemented software (see Figure 14)

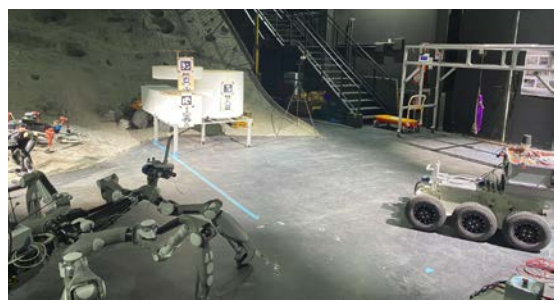

Figure 14: Mantis (left) and VELES (right) in front of the lander mock up

Along the first week, several tests based on the Agent, Infuse and Rover Guidance SW components were successfully performed with both robots (Figure 15).

Figure 15: First CREW integration tests with real robots

Both robots were commanded by the Agent using wireless communications and closing the SW loop of “sensing, planning & acting” with the final robotic platforms.

In addition to the indoor tests in the space exploration hall there were also outdoor tests. First single tests were made in CSLAM with the robots Mantis and VELES on uneven sandy terrain (Figure 16)

Figure 16: Mantis (left) and VELES (right) outdoor for first CSLM tests (credit: DFKI GmbH, T. Frank)

4.3 Final Demonstration

A final demonstration shall be performed in the Space Exploration Hall in Bremen. For this indoor lunar analogue environment it was decided to set up a testbed with regolith simulant. It will be possible to replicate realistic simulation conditions (e.g. navigation, mobility, autonomy). The final setup also includes handling logistics, working areas, power, supplies, preparing ground truth data, adjusting lightning conditions and preparing regolith surfaces.

4.3.1 Test area

The Space Exploration Hall has a total area of 288m2, a crater test area, based on a crater at the South Pole on the Moon, and a ramp at the head of the crater adjustable in its gradient degree. To replicate lunar light conditions, the inner walls have black non-reflective coating. A Vicon tracking system, with six cameras, can measure positions with a precision of less than 1 cm. The usable size of the test area will be of 10,3 x 6,9m and needs to fit all relevant elements (Figure 17).

4.3.2 Fidelity of the lunar analogue

Fidelity represents the similarities between the lunar analogue and the Moon. Two criteria considered are geomorphology and space exploration conditions. Geomorphological fidelity shows how the terrain’s materials and shape, while exploration conditions fidelity simulates settings that agents face on the Moon (eg. different light conditions).

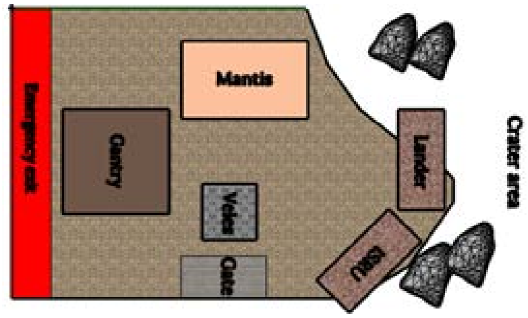

Figure 17: Analogue setup for the final demonstration with all the relevant elements.

Geomorphological fidelity includes size distribution and physical characteristics of simulant particles, the presence of rocks and boulders of different sizes and the presence of slopes and craters.

- The chosen lunar regolith simulant is a sand from the Baltic Sea basin, on the German coast, with a grain size distribution of 0 – 1mm (similar to distributions seen in Moon samples from the Apollo missions [15].
- “Fake” boulders and rocks will be used to simulate rims of young (<30 million year) craters.
- The terrain will be shaped with a mix of flat and short sloped areas (around 7.5% inclination).

5 CONCLUSION

The paper presented the PRO-ACT project, its involved robotic systems, the further development and implementation of the outcomes of previous OGs and some results of first implementation and integration on the robotic systems VELES and Mantis. It shows that outcomes of previous space robotic projects can be successful further developed and adapted to the needs of the project requirements.

For future projects the authors are sure that the outcomes of the PRO-Act project can be implemented on future space robotic systems in order to push the European space roadmap.

Acknowledgement

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[15] Carrier W. D., et al. "The nature of lunar soil". American Society of Civil Engineers, Soil Mechanics and Foundations Division 75, 813–832, 1973