# ENHANCEMENT OF THE SIX-LEGGED ROBOT MANTIS FOR ASSEMBLY AND CONSTRUCTION TASKS IN LUNAR MISSION SCENARIOS WITHIN A MULTI-ROBOT TEAM

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## ABSTRACT

Mantis is a six-legged walking robotic system that is designed for locomotion in uneven terrain as well as to perform manipulation tasks. Mantis is one involved robotic system in the project PRO-ACT (Planetary RObots Deployed for Assembly and Construction Tasks) in which different robotic systems work together to perform cooperation tasks like assembly and transport to build up lunar infrastructure, e.g. for In-Situ Resource Utilization. To support the required locomotion and manipulation skills, hardware and software modifications were conducted, which are described in this paper as well as the performed tests.

## 1. INTRODUCTION

The idea to use robotic systems for the construction of a lunar base and for the use of In-Situ Resource Utilization (ISRU) increases with the rise of Artificial Intelligence. The application of it on robotic systems allows autonomous handling by the robotic system itself in different deployment and mission scenarios on terrestrial and extra-terrestrial environments.

Within this context, the European Commission deployed a Strategic Research Cluster (SRC) on ”Space Robotics Technologies” within the H2020 research framework program. With this SRC, the European Commission is funding the agenda-driven development of core technologies for a new generation of space robots with the aim of advancing the use of orbital systems and planetary exploration. The new technologies will be used to build modular and reconfigurable satellite systems as well as robots for the exploration of Mars, Moon, and other celestial bodies. The SRC implementation is supported by the “PERASPERA (ad ASTRA)” Programme Support Action (PSA). Together with the Commission, the PSA plans the strategic goals of the SRC on Space Robotics Technologies and oversees the implementation of the respective projects, or Operational Grants (OGs)[1].

PRO-ACT (Planetary RObots Deployed for Assembly and Construction Tasks) is one of the current OGs which builds on results of previous OGs 1-5 [1]. The primary objective of PRO-ACT is to implement and demonstrate multi-robot cooperation capabilities in a moon construction context, relying on, extending and integrating the outcomes of OG1, 2, 3, 4 and 5. This includes extension and integration of the previous OGs as part of a comprehensive multi-robot system in a representative moon construction scenario and the development of robust multi-robot cooperation capabilities allowing joint interventions [2].

One planned demonstration scenario is the cooperative deployment of a mobile gantry (with a 3D printer for manufacturing building blocks using regolith of the moon provided by project partner AVS) by Mantis and the six-wheeled rover VELES from project partner PIAP Space. In another scenario Mantis and VELES will demonstrate cooperative transport, e.g. unloading the lander and installing equipment or printed building blocks at target locations as depicted in Figure 1[2].

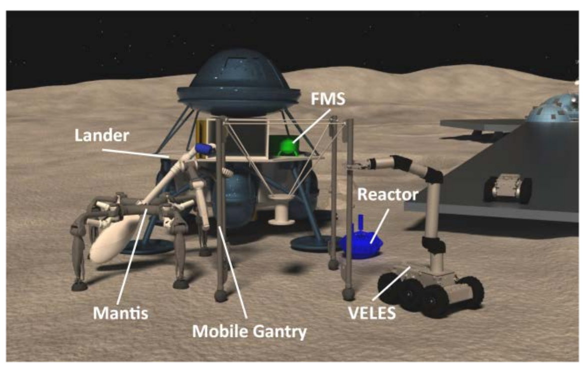


*Figure 1: Envisaged PRO-ACT mission scenario: Mantis and Veles are cooperatively unloading a lander and building up infrastructure*

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[1] https://www.h2020-peraspera.eu/
[2] https://www.youtube.com/watch?v=jNNgcgPyEO8

Mantis is a bioinspired six-legged walking robot that is developed by DFKI to explore rough terrain and to simultaneously provide dual arm manipulation capabilities [3]. Therefore, Mantis can switch between a stable six-legged walking posture (Figure 2) and, through lifting its chest, a manipulation posture that uses four rear legs for locomotion and the two front legs for manipulation (Figure 3). Mantis is equipped with exteroceptive sensors, i.e. a stereo camera and laser scanner on the head, as well as proprioceptive sensors like inertia measurement unit (IMU), six degrees of freedom (DOF) force-torque sensors on the feet and ankles, as well as joint position, velocity, current, and temperature sensors. The full sensor and actuator suit allows autonomous control of the system, but also semi-autonomous control, e.g. teleoperation with an exoskeleton [4], is possible. However, in order to support cooperative tasks within a multi-robot mission, further developments were needed, which are described in this paper.

The next section describes the improved and additional hardware components. Section 3 summarizes the software enhancements. A selection of conducted experiments is described in Section 4. The last chapter concludes the results and provides an outlook.

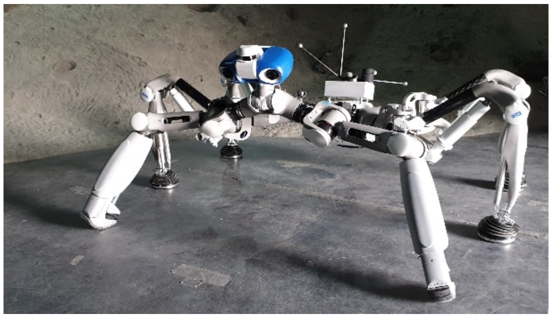

*Figure 2: Mantis in locomotion pose*

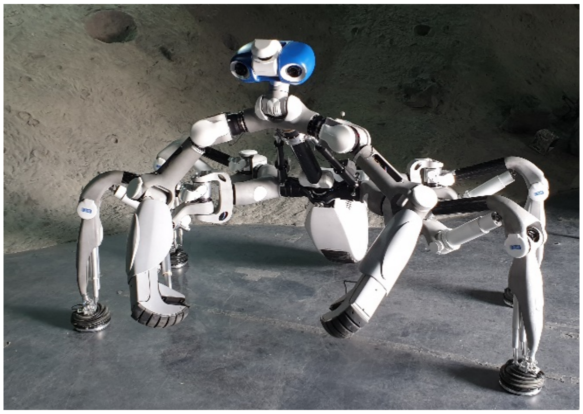

*Figure 3:Mantis in manipulation pose*

## 2. MECHANICAL ENHANCEMENTS

In order to cover the needs of the planned demonstration mission scenarios, several mechanical adaptations on Mantis are performed: 1) redesigned and integrated grippers on both forearms to support the desired dual-usage for locomotion and manipulation without manual intervention, 2) modifications of the ankle joints of the legs for increased robustness, 3) strengthening the hip linkages of each leg to support higher loads, and 4), the integration of additional hardware to build up on advanced and standardized OG outcomes to integrate Mantis into a heterogenous multi-robot team.

### 2.1. Gripper

The new gripper (Figure 4) can be used for locomotion and manipulation without manual intervention. Also, it can produce a much higher clamping force than the previous version. It is designed to manipulate payloads of 10 kg on Earth with defined grasping interfaces. The surface used for locomotion consists of cast PU-brackets on an aluminum structure. Their surface is curved along two axes so the arm can roll over during locomotion. The gripper consists of a moving clamp, actuated by a brushless direct current (BLDC) motor via a spindle drive. Objects can be grasped between this clamp and the fixed clamp on the structure. The gripping force can be measured via a force sensor between the actuator and the moving clamp. In order to control the maximum grasping force, a local control loop between the FPGA-based motor electronics and the force sensor board is implemented. Forces and torques acting on the gripped object as well as during locomotion are measured by a separate force-torque sensor located between the arm structure and the gripper.

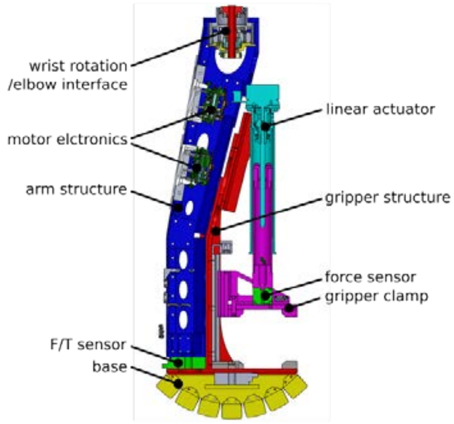


*Figure 4: CAD of the new gripper*

### 2.2. Active Multi-Contact Foot Design

Figure 5 shows the lower leg and foot design of Mantis. The lower leg provides active adjustments to roughly orientate the foot parallel to the ground to compensate orientation changes of the leg that naturally occur within the step cycle. Therefore, the cardan joint is controlled via a lightweight parallel kinematic consisting of two spindle drives that can apply large torques while consuming comparably low power. The motors of the spindle mechanism are controlled by two FPGA-based motor electronics which synchronize the joint control with each other. These two electronics measure the angles at the cardan joint directly through an absolute encoder on each axis to calculate the motor positions by an inverse kinematics model and vice versa. Therefore, it is possible to control the motors directly or provide target angles which also are converted by the inverse kinematics into motor positions. With this mechanism sensor failures can also be detected.

The actual foot is located beneath the cardan joint of the shank. It is a self-adaptive mechanism that is basically a walking surface with a ball joint on top. This ball joint rotates around a virtual center of rotation (Figure 6) which is located below the surface on which the robot is walking. Thus, the self-adaptive foot always orientates itself with the walking surface parallel to the ground within a certain range. This covers fast response to uneven and unexpected surface variations by the passive joint. The flat walking surface itself provides a large surface that minimizes sinkage into sandy substrates

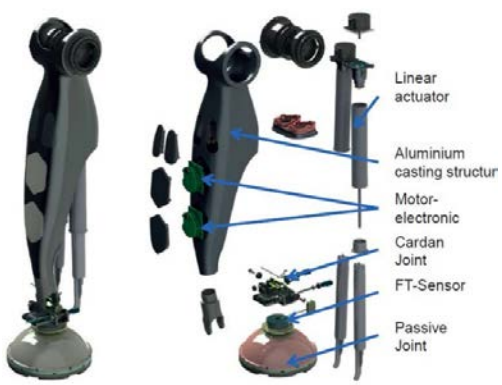


*Figure 5: Leg and foot design of Mantis*

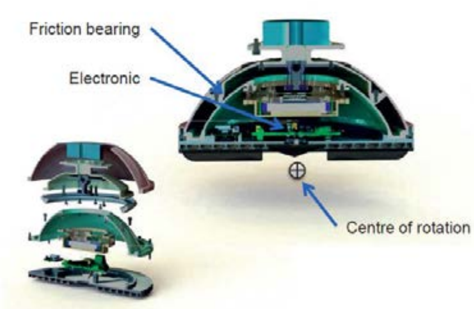


*Figure 6: Foot Design*

### 2.3. Hip Linkage

The hip linkage mechanically connects each leg with the main body. As a result of a broken hip linkage during a test run, the hip linkage was redesigned. The new design has a higher stiffness and can support higher loads than the previous version. The reference load case for the redesign was derived from force and torque measurements conducted and logged during the test run that led to the failure. Since the design features a fixed and a floating bearing, axial loads are only supported by one arm of the linkage which, combined with the relatively low stiffness is assumed to be a key factor in the failure. Accordingly, a central goal was to achieve a higher stiffness of the structure and thus better stability of the bearing. The deformation of the upper bearing with regard to the lower bearing was reduced by almost 92%, according to the conducted FEA. Also, the maximum van-Mises stress on the outside of the structure was reduced by about 82% in the critical area where one fracture occurred, marked in Figure 7.

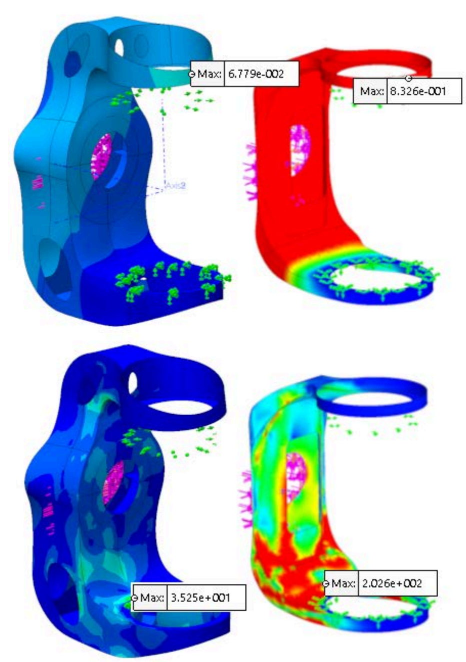


*Figure 7: FEA results of hip linkage (left: new; right: old, top: deformation in mm, bottom: van-Mises stress in MPa)*

### 2.4. Additional Hardware Components

Mantis initial design has already numerous actuators and sensors integrated that supports autonomous control, i.e. a lidar and a stereo camera as exteroceptive sensors, an inertia measurement unit (IMU) measure the orientation and acceleration of the body, a six-DOF force-torque sensor on every limb, and joint sensors to control position, velocity and current. In addition, a dedicated electronics board, the ZynqBrain, is integrated to transfer commands and telemetry between the ethernet-based control framework and the LVDS-based low level devices such as joints and force-torque sensors. The motion control is executed on a dedicated CPU.

As part of the robotic team within Pro-Act, Mantis received additional hardware. Figure 8 provides an overview over all sensor and the processing unit. The additional devices are:

- A mesh communication to replace the Wi-Fi connection for long-range and robust wireless communication.
- A high precision IMU that was tested and validated within I3DS (OG4).
- An FPGA-based instrument control unit (ICU) to preprocess camera stereo camera images with high frequencies.
- An additional onboard computer (OBC) to host the ESROCOS based data processing InFuse (OG3) as well as the ERGO motion planner (OG2).

## 3. SOFTWARE ENHANCEMENTS

Besides the constructional improvements, this paper presents Mantis' software architecture. This includes its interfaces to integrate Mantis within the multi-robot control scheme as well as insights on the provided walking gaits that are needed for the execution of the required manifold tasks.

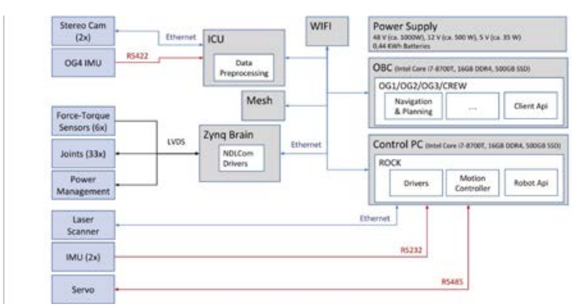


*Figure 8: Mantis sensors and electronics*

### 3.1. Control Architecture

Mantis' motion control in running on a dedicated computer to be independent of any additional software components. It is interfaced through the robot application interface (API). The OBC host the OG software libraries and their extensions. Here, the overall mission is controlled and tasks derived. From that the cooperative manipulation modules as well as the rover guidance and navigation will generate trajectories that are finally executed by the robot's motion control. Additionally, the InFuse data processing nodes are used to fuse the sensor data coming from the robot and the ICU to generate digitals elevation maps (DEM) that are used for further planning. In addition, the cooperative SLAM is computed for localizing and generating a common map by and for all involved robots.

### 3.2. Communication and Robot API

In order to provide a framework independent communication interface to on-board modules and external control and monitoring entities, the framework independent robot_remote_control library (RRC)[3] is wrapped into a ROCK task [5]. Thus, a unified com-

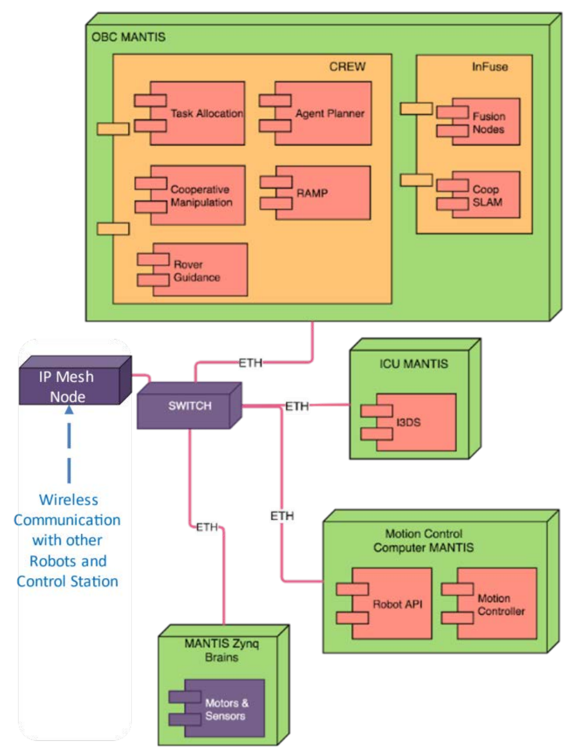


*Figure 9: Mantis Control Overview*

[3] github.com/dfki-ric/robot_remote_control

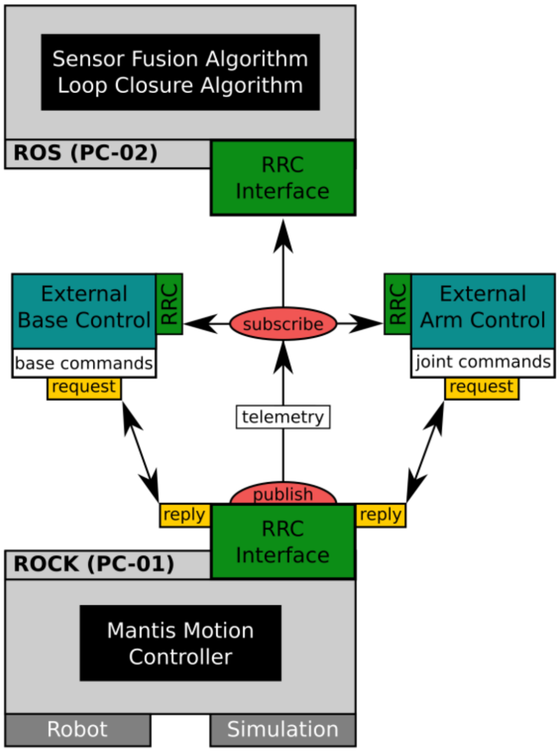


*Figure 10: Communication interface*

munication layer is established and used to facilitate exchange of data and commands to modules using other frameworks, like the sensor fusion and loop closure algorithms, which run in ROS on a second computer (OBC). The RRC library offers two configurable communication sockets, one for reliable command transfer and another one for non-blocking telemetry transport. Per default, the open-source messaging library ZeroMQ[4] is used as transport layer. This supports many-to-many connections and provides a number of connection patterns. That way, several instances may subscribe to telemetry data. In addition, a number of external controllers can be used to command different parts of the robot (Figure 10).

### 3.3. Locomotion Control Enhancements

In order to perform different tasks such as exploration or cooperative transportation on various surfaces, Mantis needs to use its full flexibility of its locomotor system. As stated in [6], the ability to use different walking gaits for different substrates is mandatory to realize an efficient locomotion. Also, hybrid rovers with wheeled legs can use this advantage as described in [7].

For Mantis, a biologically inspired locomotion approach [8] is used that is based on a central pattern generator in combination with reactive behaviors to adapt to the environment. It allows different kind of postures and walking gaits to cope with different environmental and action-specific constraints. A six-legged walking patter is implemented to walk statically stable over uneven terrain. Mantis is also capable to lift its body around its hip joints to unload the front arms having them available for dual arm manipulation tasks in an appropriate working height. For this posture, a four-legged walking gait is implemented that continuously shifts the center of mars over the intended support polygon to unload the leg that is supposed to make the next step. However, because the center of gravity shifting lowers the possible walking speed and complicates cooperative transport with another robot, a five-legged walking gait was developed. Here, one arm is used for manipulation while the second supports the locomotion. It builds a large support polygon with each diagonal leg pair, removing the need to continuously shift the body.

## 4. SIMULATION AND EXPERIMENTS

In order to efficiently develop, integrate, and test a common control approach among several involved partners, the dynamic rigid body simulation MARS[5] is used during the development and implementation phase to virtually test sensors, joints, control and software implementations on Mantis and VELES in an artificial lunar environment. In this way, errors can quickly be found with less effort and without potentially harming the physical robot systems. Additionally, it improved the collaboration between project partners especially in the Covid-19 pandemic.

After finishing early stage experiments in simulation, real experiments were conducted. Besides implementation and testing session with involved partners, also many tests were remotely performed, i.e. while most software parts were running on the robot, the commands were sent from the project partners residences across Europe, followed by offline experiment post processing. In retrospect, the remote tests can also be used as a basis of experience for space missions. These are not only carried out remotely, but there are also delays due to the distance between the earth and the celestial body concerned.

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[4] zeromq.org

[5] https://github.com/rock-simulation/mars

First, Mantis capabilities were tested with respect to the mission requirements, e.g. walking an uneven and sandy terrain or holding a load of 5 kg with the gripper. Especially, cooperatively pulling the mobile gantry apart requires large pulling force capabilities. Thus, it was experimentally evaluated, how much force can be applied to Mantis in different postures before tipping over. In the four-legged locomotion pose, in which the forearms were raised, a maximum pulling force of 380 N could be inserted. The maximum pulling force in the six-legged locomotion pose is beyond 420 N is possible but could not been tested any further. However, also the five-legged posture could withstand the 420 N while also walking backwards at the same time. Thus, pulling the gantry crane is feasible allowing to finalize its design.

Second, stereo cameras processing with the ICU were tested, followed by InFuse post-processing tests to validate the interplay between all hardware and software components to build up a DEM.

Third, integration work and intermediate tests with Mantis, VELES, and the lander mock-ups were carried out in the space exploration hall in Bremen (Figure 11). Main goal was the integration of the software developed in the project and first functional tests of the robot systems with the implemented software. The interface between ERGO path planner and Mantis' motion control has been successfully tested.

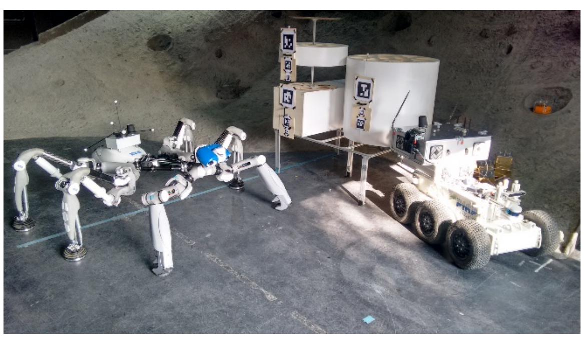

*Figure 11: Mantis, VELES, and the scenario mock-ups (fluid management system, reactor and the housing of the mobile gantry crane) during integration tests in the DFKI space exploration hall*

Furthermore Mantis performed first tests in Collaborative Simultaneous Localisation And Mapping (CSLAM) in a single test outdoor on an uneven and sandy terrain (Figure 12). 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.

*Figure 12: Mantis outdoor on uneven and sandy terrain performing first tests of CSLAM*

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 next step will be for Mantis to perform CSLAM with the other robotic system VELES together (Figure 13).

*Figure 13: Mantis and VELES prepared to work together (credit: DFKI GmbH, Annemarie Popp)*

## 5. CONCLUSION AND OUTLOOK

This paper highlights the technical and software improvements of Mantis in context of its involvement in the space robotics project PRO-ACT. The foreseen tasks are the cooperation with the rover VELES and the mobile gantry for lunar construction tasks. Thus, body parts of Mantis like the gripper, ankle joints and hip linkages are improved by new designs that are already experimentally validated.

Software enhancements allow Mantis now to perform 5 legged locomotion. In addition, Mantis is integrated in the OG hardware and software toolchain allowing a simple integration in future space missions. Additionally, all requirements are met to use Mantis within a multi-robot scenario. Preliminary tests have shown the functionality of the software architecture. The next step will be the multi-robot cooperation and handling between Mantis, VELES, and the mobile gantry in an outdoor area as well as in an indoor testbed that features fine granulate to simulate further constraints on the mobility of the systems.


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