ANT – Executive Summary Report

AUTONOMOUS NON-WHEELED ALL-TERRAIN ROVER (ANT)

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Executive Summary

This project developed a guidance, navigation, and control system for legged robots that, on the one hand, exploits the potential of legged locomotion to allow the exploration of hard-to-reach areas such as steep and rugged terrain, and, on the other hand, provides a generic approach that can be applied on systems of different morphologies, i.e., quadrupeds and hexapods. The software can be configured with reasonable amount of effort to the target system that meets the requirements for a specific future planetary mission.

The navigation system is closely coupled with the robotic motion control to be able to exploit the full potential of the mobile locomotion system. The presented solution is obeying the tight interaction while introducing a suitable level of abstraction to receive a modular and generic navigation and control system that can support different types of walking robots. This allows, depending on specific requirements of future space missions, to utilize energy-efficient four-legged as well as more stable six-legged robots, the latter featuring additional redundancy and lowering the risk of mission failure in case of damaged actuators.

Figure 1 provides an overview of the chosen architecture. A Guidance and Navigation Layer (NAV) generates a path to a given target based on the current location of the robot and the sensed environmental information that is represented in a sophisticated map. The generated path is then transformed by a Motion Control System (MCS) into precisely planned footholds that are reactively adapted to compensate for undetected irregularities. The footholds are used to plan the motion of the robot generating kinematic references for all actuated joints. A Hardware Abstraction Layer (HAL) is introduced to define a generic interface for different types of torque-controlled legged robots.

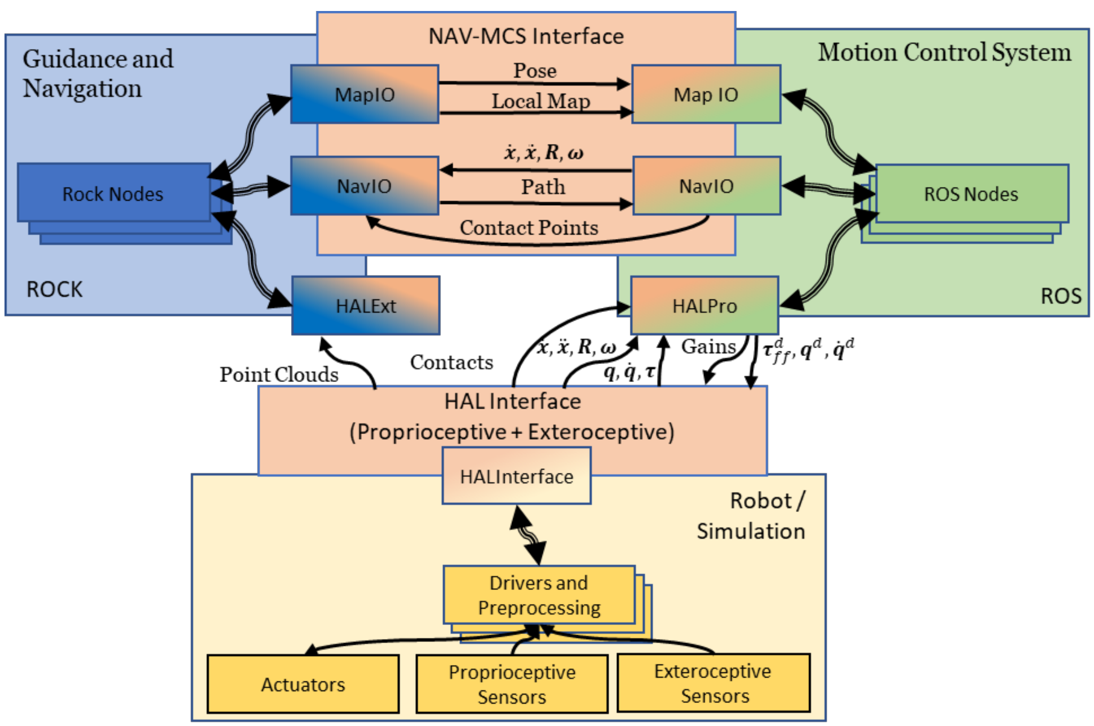

Figure 1: Overall control architecture and interfaces between main layers - The software can be deployed on one or several computers and supports implementations in different Middleware frameworks, in this case ROCK (blue) and ROS (green)

To generate the coarse path that should be followed to reach a given target destination, the NAV layer (i) perceives the state of the robot, (ii) senses the state of the environment and represents it in form of a map, and (iii) plans a path based on the acquired information. However, to fully utilize the potential of legged systems, besides using a traditional self-localization and mapping approach (SLAM), an additional local mapper is introduced to provide a high-resolution local map with high update rates to allow foothold planning by the MCS. Main components of the NAV layer are:

- Exploration module capable to explore unknown areas
- A 3D path planner for omnidirectional trajectories that consider the mobility characteristics
- A global SLAM to generate a global map and consistent pose estimation
- A local map with high resolution from visual and contact information

The MCS takes care of generating the motion of the legs and to plan and control the robot Center of Mass (CoM) position and trunk orientation. The motion of the legs is generated to connect footholds that are planned based on the navigation references (e.g. a planned path or commanded velocities) and on the knowledge about the terrain and the robot capabilities. The CoM trajectory is planned so that the robot locomotion is statically stable, i.e., the CoM is always inside a support polygon (convex hull formed by the feet in contact). The MCS makes use of proprioceptive and exteroceptive feedback. The proprioceptive feedback includes the actual robot joint positions $\boldsymbol{q}$, velocities $\dot{\boldsymbol{q}}$, and torques $\boldsymbol{\tau}$, as well as measured body velocity $\dot{\boldsymbol{x}}$, acceleration $\ddot{\boldsymbol{x}}$, orientation $\boldsymbol{R}$, and angular velocity $\boldsymbol{\omega}$, and the information whether a foot contact was detected by the force-torque sensors or not. As exteroceptive feedback, MCS receives a local terrain map around the robot. As output, the MCS provides the low-level control with desired joint positions $\boldsymbol{q^d}$, velocities $\dot{\boldsymbol{q}}^{\boldsymbol{d}}$, gains (proportional and derivative), and torques $\boldsymbol{\tau^d}$. Main components of the MCS are:

- An omnidirectional path follower creating reference longitudinal, lateral, and rotation velocities
- A generic control library that can be interfaced to support different robot morphologies
- Versatile walking gaits for quadrupeds and hexapods
- Compliance (i.e. haptic adaptation to the environment)
- Visual foothold adaptation
- Slippage detection
- Load bearing assessment

The presented guidance, navigation and control approach for legged systems was successfully implemented on two robots, the hexapod CREX and the quadruped Aliengo. Key enablers for the rapid deployment are the (i) generic implementations of the NAV and MCS algorithms that can be configured for the target systems, (ii) a docker-based deployment of the single software stacks, and (iii) the framework-independent communication between the software layers. Both systems were tested in rough, inclined, and unconsolidated terrain (as exemplarily shown in Figure 2 and Figure 3) and showed that

- Climbing 30° slopes is possible, mainly limited by the friction between feet and surface
- The torque-based control with haptic adaptation to the terrain guarantees stable locomotion in unstructured unconsolidated terrain
- In unstructured unconsolidated terrain, exploiting map information to select the next foothold has shown safer locomotion, because the desired feet positions are adjusted to maximize the safety

- Proprioceptive map updates help to maintain a up-to-date map in unconsolidated environments
- Assessing the terrain stability has been possible too, by using the load bearing assessment module making the locomotion strategy robust against collapsing terrains
- Using an omnidirectional 3D path planner and trajectory follower is required to exploit the mobility of legged locomotion systems.
- Rocks etc. are not necessary obstacles but rather useful to increase traction and should be treated as such, i.e., not avoiding obstacles in the path planning when they can be traversed and using local map information to visually adapt the foothold placing.
- High-Frequency and drift-free pose estimations are crucial to maintain an accurate map that can be used for visually guided footstep planning.

Figure 2: Walking over unconsolidated, unstructured terrain with Aliengo on the tilting platform of ALTEC's Mars Terrain Simulator with rocks

Figure 3. Walking over unconsolidated, unstructured terrain with Crex in DFKI's space exploration hall.