# WALKING AND CRAWLING WITH ALOF - A ROBOT FOR AUTONOMOUS LOCOMOTION ON FOUR LEGS

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In this paper we introduce the robotic quadrupedal platform ALoF that is designed to aid research on perception in legged locomotion. A well-balanced size and complexity of the robot results in a robust platform that is easy to handle, yet able to perform complex maneuvers as well as to carry sophisticated 3D sensors. A very large range of motion allows the robot to actively explore its surroundings through haptic interaction, and to choose between a wide range of planning options. This robot was employed and tested in the lunar robotics challenge organized by the European Space Agency, for which we also developed a novel crawling gait, in which the weight of the robot is alternately supported by scaled plates under the main body and the four shank segments. This allowed for stable locomotion in steep terrain with very loose soil.

## 1. Introduction

The advantages of legs, in comparison to other principles of locomotion, are in large part confined to difficult and rough terrain in which other locomotion systems might become stuck and fail completely. For almost all other scenarios, alternative systems (like wheels or tracks) are usually preferred, as they show a superior performance with respect to robustness, locomotion speed, and energetic efficiency, –the three factors that largely limit the operational range of mobile robots and hence their physical autonomy. While research on the fundamental principles of legged locomotion (such as dynamic stabilization, or the exploitation of natural dynamics) is highly desirable to lessen these disadvantages, the ultimate goal of legged locomotion systems must be their application in rough and highly unstructured terrain.

Recent findings have shown impressively that locomotion in such terrain is possible with the current state of the art. For example, within the DARPA learning locomotion challenge [1, 2]. However, in this project, the task of locomotion was reduced to a problem of *planning* and *execution,* as the robots were (by using an external motion capture system and pre-recorded terrain maps) at all times made aware of their exact state and the detailed shape and

properties of the surrounding terrain. In any given real application, such detailed knowledge is naturally not available and must be collected by the robot itself. This generates an additional important task of *perception*.

The intention of this paper is twofold: On the one hand, it serves the purpose of describing our newly developed research platform ALoF that is designed to aid research on perception for legged locomotion and foster the creation on systems that are able to navigate fully autonomously through rough terrain [3]. In a second part, we describe some extensions we added to this system during the Lunar Robotics Challenge (LRC) in the fall of 2008 and share the experiences we gathered there. Special attention is thereby paid to a novel crawling gait that we developed for locomotion in steep terrain with very loose soil.



Fig. 1. The *ALoF* robot during the ESA Lunar Robotics Challenge. In addition to its basic configuration it was equipped with pan-tilt cameras, lights, a dust-protection cover, and scaled plates under the shanks and the main body.

## 2. System Description

Our robot (fig. 1) is a four legged quadruped with a total weight of about 15 Kg and linear dimensions in the range of half a meter. This means the platform is small enough to be handled by one person alone, yet able to carry larger and more sophisticated sensors, as for example stereo cameras, laser range finders, and the like. Each of the legs has three degrees of freedom, allowing for hip abduction/adduction, hip flexion/extension, as well as knee flexion/extension. The three joints are set up in a 'mamalian' configuration, with the two knees facing each other. This arrangement generates more symmetrical ground contact forces, which can be exploited to reduce the joint load in certain configurations. The feet are not actuated. We limited ourselves to the minimal number of degrees of freedom, to keep the complexity low and thus increase the robustness, modularity, and ease of maintenance of the system. This is particularly desirable for a research platform.
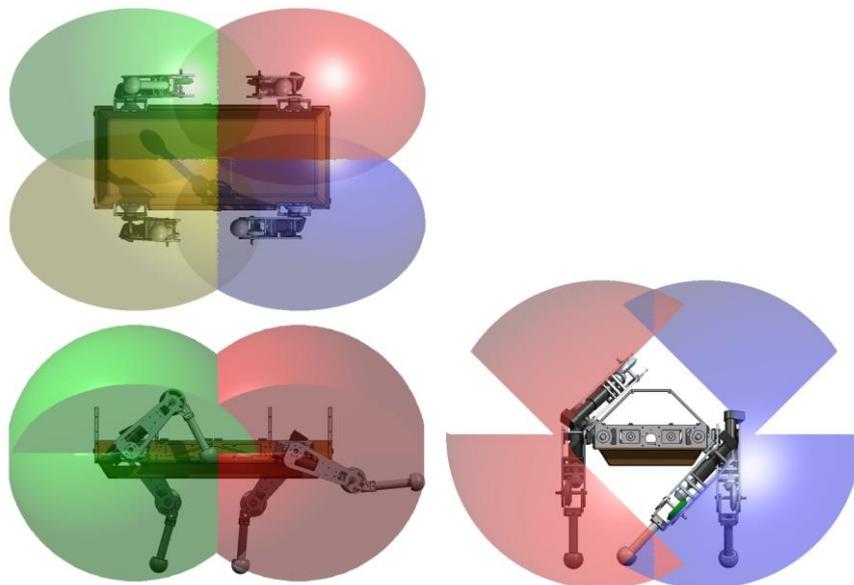


Fig. 2. A differential drive at the hip, bevel gears at the knee, and the compact, tapered design of the main body allow a very large range of motion for all four legs.

A simple bevel gear drive (with a reduction rate of 2) at the knee allows for a large motion of the knee joint, which can flex 160 deg and extend 90 deg from

a fully outstretched position. The hip is build as universal joint that is actuated by two motors connected by a differential drive system. When the two hip motors turn in the same direction, they create a flexion/extension motion of the thigh (with a reduction of 1.5) and when they turn in opposite directions, they create an abduction/adduction motion of the thigh (with no additional reduction). The two motion axes intersect in the center of the differential drive gearbox. This arrangement allows for a continuous rotation of the leg about the flexion/extension-axis (the actual range of motion is limited to 360 deg by the need for a power and signal connection to the knee-joint). The tapered design of the main body impedes hip abduction/adduction minimally, which means that this motion can reach - 45 deg and + 90 deg from vertically downwards (fig 2).

The overall large range of motion allows for a greater variation of foot placement and hence provides the robot with the necessary choices for challenging planning tasks. It additionally facilitates haptic exploration of the terrain, and enables the execution of alternative gait patterns or recovery maneuvers. This includes, for example, the task to stand up after falling down, which adds an intrinsic robustness component to the locomotion task. Finally, this large range of motion makes it possible to move the legs forward and backward while the robot is sitting on its main body, which allows us to perform the crawling gait described later in this paper.

To be able to actually exploit this large range of motion, we equipped all joints with strong actuators. 12 DC motors (Maxon RE25, 24V) with a gearbox ratio of 79:1, (which is additionally amplified by the bevel-gears) generate enough torque in the legs to lift about four times the weight of the main body when standing up from the ground. 12 individual servo controllers connected by a CAN-bus take care of low-level velocity/position control and are controlled by a NI single-board RIO, which combines a FPGA-controller and a real-time processor for the different layers of data acquisition and control. This controller is connected to a host-computer via a UDP/IP connection. High level control and energy-supply are provided off-board to save weight and reduce the complexity, however, due to the large payload abilities, batteries could be included on-board. The detailed hardware characteristics are listed in table 1.
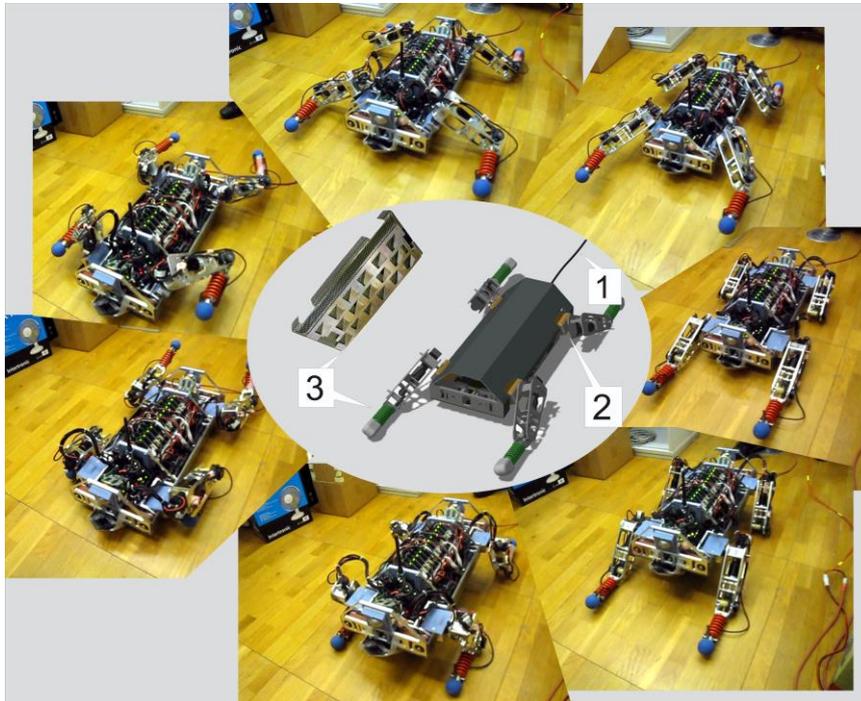
Fig. 3. The main task of sample return in the LRC was performed by ALoF, which was suspended by a tether-cable (1). The large range of motion joints at the hip (2) allowed the robot to walk upright, but also to perform a crawling motion while keeping the center of mass low. On the slopes of the crater, the crawling motion was supported by scaled plates (3) under the main body and shanks. The video stills at the outside illustrate the crawling motion (clockwise = forward crawl).

## 3. ALoF at the Lunar Robotics Challenge

The Lunar Robotics Challenge (LRC) [4] evaluated and compared different robotic systems that were build to collect soil specimens in a simulated lunar crater and return these samples to a simulated lander module. With regard to locomotion, the main challenge of the contest lay in the very steep terrain at the slopes of the crater, which was additionally covered with loose soil, rendering standard wheeled locomotion systems useless. The teams had additional to cope with challenging lighting conditions and the missing line-of-sight between the

lander and the bottom of the crater. This made navigation, control, and communication extremely difficult.



Fig. 4. Close-up view of the scaled plates under the main body and shanks that dug deep into the loose soil and stably supported the robot, even in the steep slopes of the simulated crater.

The team of ETH Zurich implemented three collaborating robots that jointly tackled this challenge. The main task of descending into the crater, collecting the sample, and returning it to the lander was performed by ALoF. Some modifications and extensions to this robot were made specifically for the challenge: It was equipped on both ends with a Pan-Tilt camera and bright illumination to enable controlling via a remote operator. As, unlike in wheeled systems, no continuously rotating parts exist, it was possible to cover the entire robot in a sealed fabric (a sort of 'jumpsuit'), that excluded dust and small rocks (which is shown in fig. 1). This only slightly impeded the motion of the legs and didn't alter the range of motion. The communication link with the host-computer was established by a wireless connection, over which the robot was remote-controlled from a ground station that commanded individual steps or step-sequences.

Table 1. Hardware characteristics of the ALoF robot.

| Parameter | Value | Parameter (cont.) | Value |
|---|---|---|---|
| Overall Length | 557 mm | Spacing between hip joints (longitudinal) | 389 mm |
| Typical Height | 400 mm | Spacing between hip joints (lateral) | 208 mm |
| Overall Width | 386 mm | Length of Thigh Segment | 150 mm |
| Total Mass | 15 Kg | Length of Shank Segment | 150 mm |
| Main Body Mass | 10 Kg | Foot diameter | 40 mm |
| Torque Knee (continuous/peak) | 4 Nm / 15 Nm | Maximum peak load for standing up from the ground | 400 N |
| Torque Hip (continuous/peak) | 3 Nm / 11.3 Nm | Range of motion for hip flexion/extension | $\pm180$deg |
| Range of motion for hip abduction/adduction | -45 deg / +45 deg | Range of motion for knee flexion/extension | -160 deg / +90 deg |

During the entire mission, ALoF was attached to a safety cable which was deployed from a second stationary robot at the landing module. The cable was used to passively stabilize the robot on the slope, to enhance its climbing capabilities, and to supply the necessary energy. A third robot, a 6-wheeled rover, was driving directly up to the crater rim, where it was used as bridge for wireless communication. Equipped with a high resolution pan-tilt-zoom (20x) camera, this robot also provided an advantageous birds-eye view of the crater area which greatly facilitated orientation and navigation. The rover was equipped with the CRAB passive suspension system [5], that is optimized for locomotion in rough terrain. For communication, we relied on a two-step

wireless 802.11g bridge (relayed from the landing platform to the quadrupedal robot via the wheeled rover).

In highly unfavorable terrain (such as on the slopes of the crater), due to its large range of motion, ALoF was able to lower itself onto its main body and switch from a regular static walking gait to a crawling or sliding motion (fig. 3). This allowed the robot to inch itself up or down the crater, even on extremely steep slopes. In this mode, the body weight was either supported by all four legs at once (when moving forward), or by the main body (when retracting the legs), thereby increasing the overall area of support. By equipping the robot on the bottom side of its main body and shanks with scaled plates, further measures against slipping, sliding, or caving in were introduced (fig. 4).

This crawling concept performed exceptional well in the demanding environment of the challenge. The scaled plates under the main body and shank segments dug deep into the loose soil and stably supported the robot, even in the steep slopes of the simulated crater. The only issue not fully satisfactorily solved, was lateral motion. The scales were optimized for forward motion and created only little resistance when employed laterally. This led to unwanted drifting when the robot crawled on lateral slopes and reduced the angular motion when turning. The drift also corrupted odometry, as the robot was turning and sliding downhill, when commanded to move in a straight line. During the challenge, it became apparent that the crawling quadruped didn't require the tethered support at all; not even on the slopes of the crater. The tethered solution was, in retrospective, an unnecessary complication.

## 4. Conclusion

In this paper, we introduced the ALoF robot, a mid-sized research platform that is intended for the study of perception in legged locomotion. This platform was employed and evaluated during the Lunar Robotic Challenge, for which we implemented a novel crawling gait that allowed steady locomotion on steep surfaces covered with very loose soil. While the task of the LRC was not a direct application of perception (all high-level commands were directly given by the operator in the ground station), it served as an excellent test to assess the robustness and usability of the robot in a highly demanding environment.

In collaboration with the University of Southern California, we are currently implementing the SL simulation and real-time control software package [6] in the ALoF host computer. This software includes modules for robot control, simulation, and visualization, and can communicate with the actual robot via a UDP/IP connection. Implementing this framework enables us

to use the code developed at USC for the learning locomotion challenge [7], and thus rapidly create the necessary abilities for *planning* and *execution* locomotion tasks with the ALoF robot, making it possible to use the robot directly for the intended research on *perception*.

## Acknowledgments

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