TOWARDS WALKING ON MARS

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ABSTRACT

This paper presents a quadruped robot that enables novel locomotion concepts for extremely rough terrain. The system was built for upright walking but its wide range of motion in all joints allows switching to a turtle-like crawling gait when loose soil or steep slopes are encountered. Furthermore, a robust design paired with special manoeuvres that allow recovering after tipping over make the system very robust against "mission failure". The platform was initially tested in the ESA Lunar Robotics Challenge 2008 and since then further developed for completely autonomous operation in rough and unknown terrain.

1. INTRODUCTION

In 2008, the European Space Agency (ESA) organized the Lunar Robotics Challenge (LRC) in Tenerife to simulate a mission on the moon [1,2]. The task was to deploy a robot from a landing site located close to a crater, climb into the crater, collect a sample, and return to the landing base. The background behind this simulated mission is to examine the assumption that hydrogen rich ore may be found on the crater ground where no sunlight reaches. Scientists believe that in these depths of lunar craters water might be preserved frozen which could be crucial, if one day mankind wants to establish a permanent base on the moon. The conditions encountered in such a crater make exploration very different from common missions. The crater edge is extremely steep (about 40°) and will be covered by rocks, boulders, and terraces. Landslides can occur every time the sand on the crater's slope is touched. Everything that makes the crater interesting for science (no sunlight, cold temperature, depth) makes it hard to explore.

Facing these harsh conditions, the usual approach of using a wheeled rover is pointless. The rover would grave itself into the loose gravel while trying to climb the crater slope and would not be able to overcome high obstacles such as rocks. Therefore, new platforms with new locomotion principles are required for such situations where wheeled rovers can no longer operate.

We propose a highly agile, fully actuated quadruped platform with a total of 12 degrees of freedom (DoF) to perform such tasks. The robot walks upright on solid surface by careful foothold planning (Fig. 1), but switches to a turtle-like crawling gait when it comes to loose gravel and soil and/or extremely steep slopes. This special gait features a larger contact surface in combination with a very low positioned centre of gravity (CoG) that ensures static stability even under conditions as encountered in the LRC. In case of failure, the presented platform is able to recover from a complete rollover due to the impressive range of motion that is achieved by a differential drive in the hip joint.

Figure 1: The robot during walking at the testing site of the El Teide during the LRC in Tenerife 2008.

While during the LRC an operator manually selected gait parameters like speed or turning rate, the platform was subsequently equipped with a real-time simulation and planning software for autonomous operation. Gait or even more foothold selection can now be based on camera and haptic feedback.

2. SYSTEM DESCRIPTION

We developed a quadruped robot with a total weight of about 15kg and linear dimensions in the range of 0.5m. The proposed platform combines a lightweight structure with powerful actuation that makes it not only well suited for a lunar mission but also easy to handle by a single operator as a research platform. With a payload capability of more than 5kg (for a standard walking gait, largely increased for crawling gaits), the robot is able to collect as well as to transport respectable amounts of specimen, but also to carry

Table 1: Hardware characteristics of the quadruped

Parameter	Value
Overall Length [mm]	557
Typical Height Walking [mm]	400
Typical Height Crawling [mm]	120
Total Mass [kg]	15
Main Body Mass [kg]	10
Overall Width [mm]	386
Torque Knee, (Continuous/Peak) [Nm]	4/15
Torque Hip, (Continuous/Peak) [Nm]	3/11.3
Range of Motion for Abduction/Adduction [°]	±45
Range of Motion for Hip Flexion/Extension [°]	±180
Range of Motion for Knee Flexion/Extension [°]	+90/-160
Spacing Between Hip Joints (Longitudinal) [mm]	389
Spacing Between Hip Joints(Lateral) [mm]	208
Length of Thigh Segment [mm]	150
Length of Shank Segment [mm]	150
Foot Diameter [mm]	40
Maximum Peak Load for Standing [N]	400

large and sophisticated sensors. With regard to the harsh environment that the robot faced in this challenge, the chassis is built of carbon-kevlar hybrid fibres, granting for high torsional stability as well as for good robustness against collisions with a minimal mass.

2.1. Actuation

The robot shows a total of 12 degrees of freedom - 3 per leg - which are split into one DoF in the knee and two in the hip. A bevel gear drive in the knee allows for flexion and extension of about +90° and -160° respectively. Hip abduction/adduction and flexion/extension is realized using a differential gear drive (Fig. 2) which couples two actuators and enables

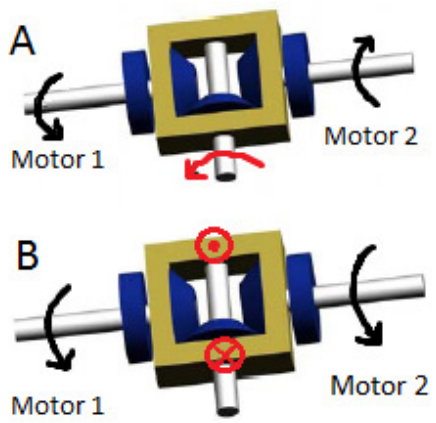

Figure 2: The upper picture shows the movement that results when the motors (black arrows) of the differential drive turn in different directions. The output shaft mounted on the hip, starts to rotate (red arrow) resulting in the flexion/extensiont. When both motors turn in the same direction the whole cage of the differential drive moves (red circles), which refers to the abduction/adduction leg (shown in the second picture).

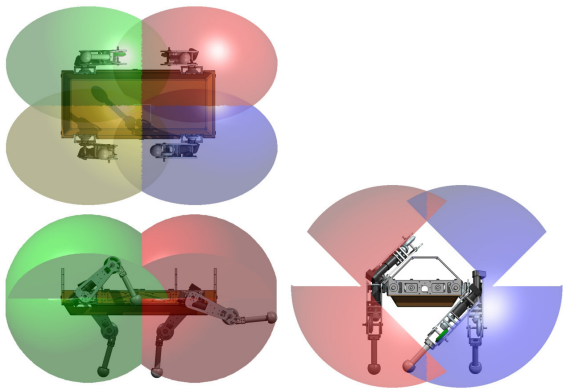

Figure 3: The wide range of motion accessible is provided by the differential drive at the hip as well as the functional design of the body

a wide range of motion of about ±180° for flexion/extension (Fig. 2A) and ±45° for abduction/adduction (Fig. 2B). This maximizes the robot manoeuvrability (Fig. 3) which is crucial when it comes to traverse challenging terrain. As a second beneficial effect, both hip motors are placed within the main body such that the leg segment mass is reduced and the motor and gearboxes can be entirely sealed from the environment (dust protection). To be able to utilize this large range of motion, the robot is equipped with 12 DC motors (Maxon RE25, 24V) with a gear-box reduction ratio of 79:1. The detailed mechanical specifications are summarized in Tab. 1.

2.2. Electronics and control

Within the Lunar Robotics Challenge, the robot was manually controlled using an external Laptop which is linked by an IEEE 802.11 Wi-Fi connection to the onboard single-board RIO (sbRIO) from National Instruments (NI) that combines an FPGA and a real time processor. The user can apply certain high level commands, such as heading, velocity, or gait transmission by using a joystick. The movement itself is generated by following pre-implemented velocity and position trajectories on the sbRIO. The sbRIO communicates over a CAN-bus system with the low level Maxon EPOS motor controllers that are responsible for velocity as well as current control. Energy supply is provided off-board by a cable which was additionally designed to hold as a tethering device for active support when the terrain is too steep.
Following pre-planned trajectories clearly limits the variability of the robot and requires for a human operator. Subsequent to the LRC, the manual operator was replaced by a simulation and planning environment [3]. This allows for real time motion as well as foot hold planning based on various sensor feedback that can monitor the main body position/orientation (IMU) as well as the environment

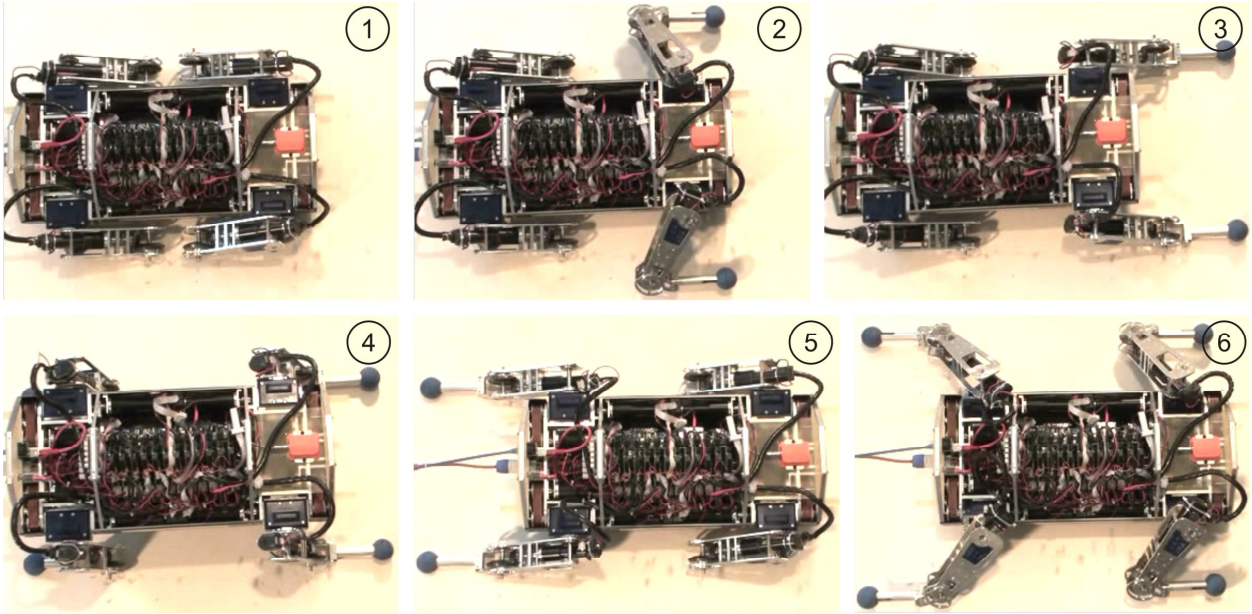

Figure 4: The large range of motion especially in the hip joint allows for unconventional gait creation such as crawling. The robot abducts the thigh about 45° ((4) and (6)) to propulse itself in a turtle-like manner which is useful to explore hard accessible terrain.

(stereo cameras, kinect sensor[4]).

2.3. LRC setup

The challenging environment with a steep crater with loose gravel and soil, no direct line of sight from the operator to the robot, no GPS availability for localization, as well as the bad illumination conditions during night required additional means for a completion of the proposed task. Our team tackled these problems by a collaboration of the presented quadruped with two additional robots. CRABli [5] (Fig. 5, on the left), a six wheel rover equipped with a passive suspension system optimized for rough terrain, was positioned at the crater edge to establish the communication link as well as to provide birds-eye view of the crater using a high resolution pan-tilt-zoom (20x) camera. A stationary robot remained at the landing station and was responsible for cabling and for support during ascending in the steepest slope.

For sample detection, the quadruped robot was equipped with pan-tilt cameras and bright illumination at both ends. Due to the challenging ground, the whole robot was sealed with a sort of jumpsuit to protect it from dust. Additional skid plates underneath the main body and the shanks improved friction and kept the direction while climbing the high inclined slopes.

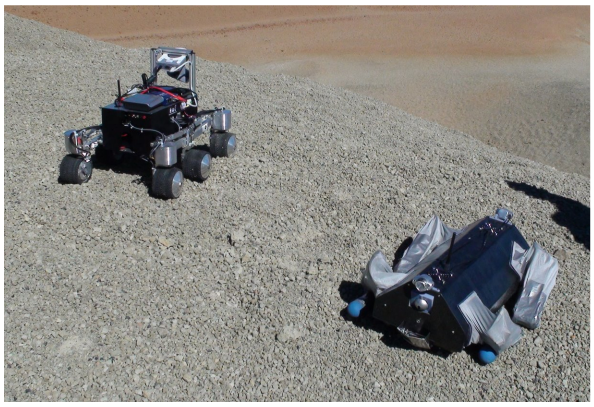

Figure 5: The quadruped and the supportive wheeled rover CRABli in front of the crater rim at the LRC testing site in Tenerife.

3. LOCOMOTION

3.1. Gaits

The high range of motion in all joints pays out in a large variety of gaits that can be applied depending on the terrain properties:

A) Upright walking

For locomotion on solid ground, a standard walking

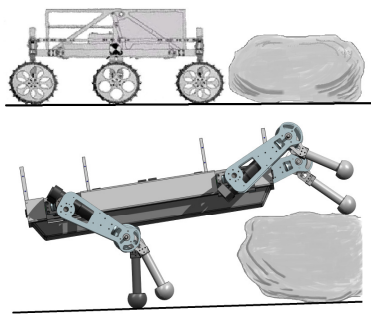

Figure 6: Obstacles of the size of the wheel diameter of the rover are mostly insurmountable obstacles, whereas for legged exploration platforms such barriers can be managed.

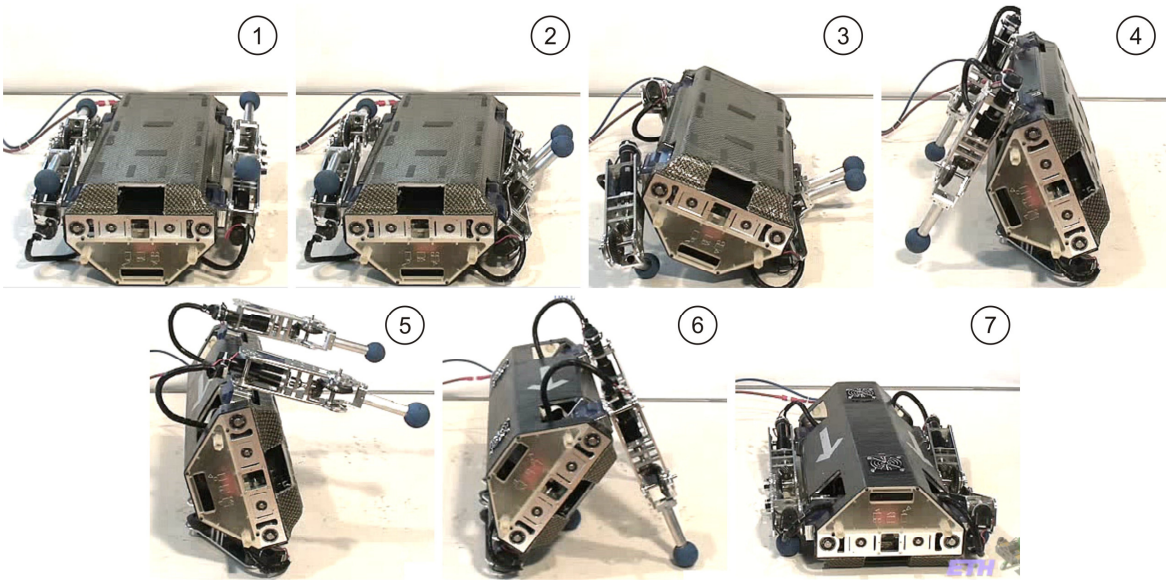

Figure 7: The picture sequence shows a rollover of the robot after tilting on its back. The first step is to position the legs of one side such that a support area is built on which further actions can be performed (frame 2). The second step is to position the main body above the support area by pushing with the legs of the other side (frame 3 and 4). Afterwards the unloaded legs are turned to the belly-side of the robot (frame 5). Using now the loaded legs to turn the torso and the upper legs to buckle (frame 6), the robot reaches its initial position (frame 7) from which it can start walking or crawling.

gait is applied with a step length of about 0.2m and a ground clearance of 0.25m. Thereby the overall CoG respectively ZMP (Zero Moment Point) [6] is kept within the support polygon of the 3 supporting feet while the swing leg is moved to the subsequent foothold position. This gait is especially interesting when large but solid obstacles or gaps in the ground must be conquered – where this robot has clear advantages compared to a same sized rover due to a ground clearance that is in the range of the leg length (Fig. 6)

B) Crawling

Upright walking becomes inappropriate when it comes to loose soil and/or landslide (which both were encountered in the LRC). The feet would sink into the ground, causing the robot to stumble and fall over. Inspired by nature, a turtle-like crawling gait was adopted that keeps the CoG at the lowest point possible (Fig. 8). The support surface is largely increased since at every instant in the whole gait cycle, either the entire main body or all four shank plates are in ground contact. The larger contact surface is additionally beneficial considering sinking in the loose soil. Fig. 4 shows a picture series of a single crawl cycle on flat ground. The required joint positions (especially (2) and (6)) are only achievable due to the high range of motion of the hip joint (differential drive).

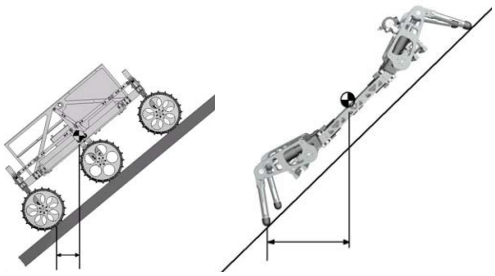

Figure 8: The static stability margin left in a steep slope situations is higher for the legged application (shown in an arachnoid configuration on the right). The system is more robust against disturbances and dynamic effects compared to the rover on the left side.

C) Specialized manoeuvres

The biggest challenge for planetary exploration devices is to recover from situations where the robot is stuck and can no longer be operated. The worst case is a complete tilt over on the top of the robot, which generally means that the mission fails, at least for a rover. The presented quadruped platform can cope with this situation: First, actuators, sensor and electronics will survive the roll-over since they are protected either by the side plates of the thigh or the shock resistant carbon-kevlar main body hull. Second, the high manoeuvrability allows recovering from any configuration (lateral or supine position) by performing the motion depicted in Fig. 7.

3.2. Terrain classification

During the LRC, the operator decided what gait should be applied depending on the ground characteristics, namely inclination, material consistency, or obstacle occurrence. Towards more autonomy, the robot has to select gait, speed or foothold on-line depending on visual and/or haptic feedback of the environment. Using the presented quadrupedal platform, we developed a haptic terrain classification algorithm [7] which can identify the decomposition of the soil and the small scale surface geometry with a high success rate. During a test cycle for which the robot has to stand on point, the foot executes a movement similar to scratching while measuring the resulting forces with a force sensing device embedded in the foot as well as the sinkage rate and motor current. Different features were extracted from this data and used for training and classification by a multiclass AdaBoost [8] machine learning algorithm. In preliminary test series, the robot could correctly classify about 94% of the terrain shapes and about 73% of the surface samples. Depending on the material (solid/compliant and the gravel size of the compliant material) a gait can be chosen suiting the current environmental conditions.

4. CONCLUSION & OUTLOOK

The presented platform and locomotion principles demonstrated that legged robotic systems are a promising approach for future exploration missions. The high manoeuvrability increases the versatility of the system, such that very challenging (in terms of obstacles, inclination, and surface characteristics) terrain can be safely traversed. Within the Lunar Robotics Challenge, we proposed a successful crawling gait that can cope with extreme slopes in combination with loose gravel and soil. In addition thereto, our quadruped demonstrated high failure robustness: even in the worst case of a complete tilt over, the robot is able to recover.

Within the LRC, gait selection (including speed, turning angle, step length, crawl/walk/...) was chosen by an operator. In subsequent research conducted at our lab, a simulation environment for foothold planning and execution was integrated that the system can operate autonomously. We are now at the stage where camera feedback in combination with IMU data are fused to estimate the robots position in unknown environment as well as to map the environment. This is augmented by haptic feedback from the force sensors for optimal foothold planning with regard to shape and consistency of the environment – leading to an autonomous quadruped robot for future explorations.

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