SpaceClimber: Development of a Six-Legged Climbing Robot for Space Exploration

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Abstract

In this paper, we present the SpaceClimber[1] integration study, a six-legged, bio-inspired, energy-efficient, and adaptable free-climbing robot for mobility in steep gradients. The long-term vision is to provide a system for the purpose of extraterrestrial surface exploration missions paying special attention to mobility in lunar craters in order to retrieve or analyze scientific samples from the interior of these craters. We present an envisaged mission for SpaceClimber and give a description of the system's morphology and the design steps. Apart from hardware design, parts of the control software as well as the utilization of evolutionary algorithms for both morphology design and locomotion control are presented.

1 Introduction

Sample return and in-situ analysis missions are of special interest in space exploration. Currently, Moon and Mars are the predominantly interesting places for extraterrestrial research. Recently the Moon came to special focus since several satellite missions in the 1990s suggested the presence of water ice in permanently shadowed areas at the lunar polar regions [1, 2]. More recently, NASA announced the detection of vast amounts of water ice at both lunar poles [3, 4]. With satellite missions, however, it is only possible to detect water (ice) indirectly. For direct confirmation of the presence of water ice at the lunar poles, an in-situ observation has to be undergone. This demands bringing a robotic device into the permanently shadowed regions since sending humans on such a mission is both too risky and involves greater mission costs.

There are several groups suggesting a multitude of possible robotic solutions to access the scientifically interesting, yet hard-to-access regions on Moon and/or Mars. Barlett et. al [5] propose a mobile robot for direct deployment at the bottom of permanently shadowed craters at the lunar poles. Since the Scarab rover will operate in permanent darkness, the proposed energy source is a Radioisotopic Thermoelectric Generator (RTG). The rover design comprises a four-wheeled active chassis suspension system for adapting the ground clearance of the robot. The robot is meant to operate on a kilometer scale; in order achieve an appropriate sampling distribution, a minimum of 25 sampling sites is aspired. The mass of the system is around 280 kg.

The robot CESAR (Crater Exploration And Sample Return Robot) [6] proved in ESA's *Lunar Robotic Challenge* (October 2008) that a hybrid, legged-wheel approach is a sophisticated method to retrieve samples from within a crater. The robot was the only one in the field of the challenge to meet all mission objectives. It succeeded in fetching 100g of colored sand out of the crater and was able to deliver the sample at a designated place.

Figure 1: Art drawing of the envisaged SpaceClimber prototype (without sensor head)

Huntsberger et al. [7] propose a reconfigurable rover team for gaining access to areas that can not be accessed with current rover designs as so far deployed on Mars or Moon. Their system TRESSA (Teamed Robots for Exploration and Science on Steep Areas) consists of a closely coupled rover team, consisting of a "cliff bot" and two "tether bots". The cliff bot is equipped with a scientific instrument package mounted on a robotic arm. To gain access to very steep areas, the two tether bots are fixed at the top of the steep slope to be investigated. The two tether bots then let the cliff bot down the slope on their tethers. Huntsberger et al. proved to be able to cover terrain with slopes of up to 85° with their system. The cliff bot is in the 8 kg rover class, the two tether bots are in the 10 kg class, [8].

Free climbing robots, however, have the advantage of not being limited to a certain length of rope. Additionally,

[1]The project SpaceClimber is funded by the German Space Agency (DLR, Grant number: 50RA0705) and the European Space Agency ESA (Contract no.: 18116/04/NL/PA)

ISBN 978-3-8007-3273-9

with progress in the development they will eventually be able to climb freely in vertical planes. In the recent past, multi-legged robots have already demonstrated a very high mobility in rough and uneven terrain. In comparison to wheeled and tracked vehicles, they provide a superior flexibility in their locomotor system. They are able to walk omnidirectionally, turn on the spot, and walk curves with variable radius. The fact that the foot looses ground contact in the swing phase of a step cycle allows them to surmount obstacles and to avoid the "bulldozing effect" wheeled and tracked systems have to grapple with on loose substrates. The ability to shift their center of mass by changing the posture (e.g. crouch/stretch or lean backward/forward), without suffering the loss of mobility, also enables them to master steep inclines.

In [9], an approach to combine the advantages of wheeled systems and legged systems for lunar crater exploration is presented. A wheeled rover is used for energy-efficient locomotion on moderate terrain. When it comes to investigating steep terrain, i.e. the interior of a crater, a legged scout is deployed in order to exploit the high mobility of the legged vehicle. The SpaceClimber robot (see **figure 1**) being presented in this paper is a possible scout for such a heterogeneous exploration system.

Beside the technical description of the components and the overall system, the morphology determination process which involved the use of evolutionary strategies, and the behavior-based locomotion control approach using a combination of postural, pattern-generating, and reflex behaviors are explained in this paper. Subsequently, first experimental results will be discussed and an outlook on planned improvements is presented.

2 Envisaged Mission Scenario and Resulting System Requirements

The requirements on the system to be developed arise from the envisaged mission scenario and the environmental conditions the system has to cope with.

As already mentioned, there is a large scientific interest in exploration of the permanently dark interior of craters in the lunar polar regions to prove the existence and the geological composition of water ice on the moon. Thus, we assume a robot-based mission with the goal to perform in-situ analysis within or sample return out of this regions. Consequently, the SpaceClimber has to provide the mobility to climb up the crater rim (ca. 15° inclination) and descend the crater wall with an inclination between 30° and 40° to reach the permanently dark region. After selecting and positioning to a sample, the robot has to make use of an appropriate payload to analyze or to collect it. Thereupon the system has to climb out of the crater to return to its base station. In addition to locomotion in steep inclinations, the system has to be able to negotiate or circumnavigate rubble which occurs with a high concentration in impact crater regions.

Beside the task-based demands the system has to face, it will have to withstand the environmental conditions on the moon. The whole surface is covered with regolith, a fine-grained and sharp-edged sediment which has to be considered very aggressive regarding system mechanics. In addition, the Moon has no atmosphere resulting in high radiation, vacuum, high temperature variation, and bad heat transmission. The only advantage over a terrestrial mission is the reduced gravity on the moon which is just one sixth related to the earth. Hence, since first of all, the system has to demonstrate its capabilities in a laboratory environment on earth, this advantage cannot exploited yet.

Furthermore, the robot has to be transported to the area of operation. Irrespective of the launch vehicle, the transportation costs per kilogram are very high and the overall weight of the payload to be launched is limited. Hence, the weight and stowing volume of the system must be kept as small as possible.

The following paragraphs give an overview of the resulting system requirements.

Mission-Based Requirements

To accomplish the mission successfully, the SpaceClimber has to

- provide mobility in slopes with inclinations of up to 40°
- walk on loose, fine-grained substrate
- negotiate obstacles of up to 40 cm height
- navigate semi-autonomously
- have an operational range of at least 1 km (low energy consumption)
- be equipped with an appropriate payload
- weigh below 20 kg
- have a small stowing volume

Environment-Based Requirements

To withstand the environmental conditions, the system has to

- be equipped with a robust housing (dust, collisions)
- have shielded cabling (radiation)
- be able to work in shadowed areas
- be space-qualifiable (through minor revisions)

3 System Design

The requirements resulting from the envisaged mission scenario [10] as well as experiences gained from the work with the formerly developed walking robots SCORPION [11] and ARAMIES [12] were crucial criteria for the mechanical and electrical design of the integration study (see **figure 5**).

In this section, we will describe the morphology determination procedure as well as the mechanical and electrical design of the developed components and the SpaceClimber integration study.

ISBN 978-3-8007-3273-9

3.1 Morphology Determination

At the beginning of the design procedure, the morphology of the system had to be defined. Even though it was preliminarily defined that the system should have six legs, which is a good compromise regarding stability, redundancy, and energy consumption, the quantity of possible configurations still remained unlimited. Based on experience gained from former projects, the basic kinematic structure of the leg with four active degrees of freedom was defined as shown in **figure 2**. This configuration allows a high reachability of positions in the energy-efficient insect like M-shape. To make use of the advantage of this shape in steep inclines, the leg can be rotated around the mounting point to stay in line with the vector of gravity.

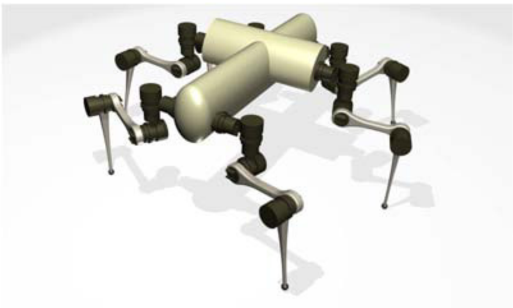

Figure 2: The final morphology of the SpaceClimber robot

To determine the length of the leg segments as well as the size of the body and the positions of the mounting points, a simulation-based optimization and design procedure utilizing evolutionary computation was developed [13]. This way, it was possible to generate and evaluate a great variety of possible morphologies.
A parameterized model of the system was created within simulation. The vector of adaptable parameters contained the mounting position of the legs, the length of the leg segments, and several parameters that influence the locomotion control of the robot. Each parameter set chosen by the evolutionary algorithm [14] was tested in the simulation by three test setups. In the first setup, the robot had to walk for 30 seconds on a planar surface with different contact friction values every two meters. In the second setup, the robot had to walk (climb) for ten seconds into a slope of 30 degrees inclination and in the last into a slope of -30 degrees inclination. The fitness value for the evaluation of the individuals was based on a combination of the overall energy consumption, mechanical stress, and stability of the system over all setups. Within 85 evolutions, each containing about 3000 evaluations, a total number of about 255000 possible morphologies were generated and evaluated. In the end, the best individual of each evolution was classified in groups with similar models. The average fitness value of the biggest group was also the best of all groups. Thus, an average individual of that group was calculated and it was assumed as the best base morphology. The finally selected configuration shown in figure 2 was used as basis for the system design.

3.2 Final Design

In this section, we will describe the component and overall system design of the integration study. A summary of planned improvements for the prototype will be given in section 6.

Actuator
The integration study of the SpaceClimber robot comprises 24 actuator modules which is why these can be considered as the core components of the system. Each actuator is built up identically in order to simplify space qualification procedures in further steps.
During the design of the SpaceClimber actuator, the chosen electronical parts as well as the mechanical construction were made with the goal to use parts that are already space qualified or easily space qualifiable or replaceable by space-qualified components.
For the core rotor and stator components of the brushless dc motor, modules from RoboDrive were chosen, as these have already been successfully space qualified [15]. The gear was chosen from Harmonic Drive, as this company has already accomplished several space qualification processes for their gear components. During the design process of the mechanical structure, special attention was paid to the requirement to construct a dust-proof compartment to withstand the harsh environmental conditions in lunar environments. The special outer structure of the actuator compartment (see **figure 3**) leads both to weight reduction and heat transmission of the components.
The core electronic component which undertakes tasks like direct motor control, current, speed and position control, real time logging of sensor data, and communication between other actuators and the central processing unit is built up by a Xilinx Spartan 3 FPGA which can be easily replaced by space-qualified FPGA modules. Further details about the components and system architecture of the SpaceClimber actuator can be found in [16].

The main specifications of the actuator are a weight of 525 g and a repeatable peak torque of 28 Nm at 0.6 Hz. The size of the actuator is 64 mm in diameter and 110 mm in length. This results in a weight-to-torque ratio of 0.02 kg/Nm. Due to the design, the maximum joint angular range of motion is 720 degrees. This range is only limited by the wire loom that is routed inside the actuator. The nominal power of the BLDC motor is 140 W. Experiments showed that the actuator operates with constant torques of 23/16/12 Nm realized with a constant speed of 3 rpm resulting in a power consumption of 30/18/13 watt.

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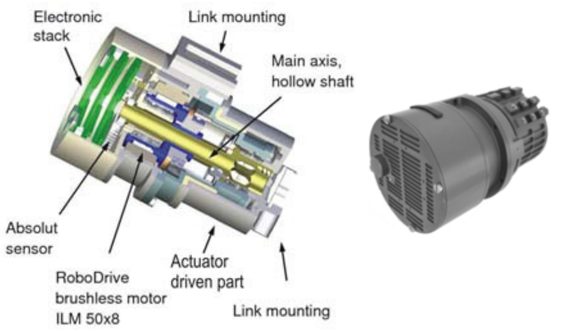

Figure 3: Labeled CAD drawing (left) and picture of an integrated actuator module (right)

The actuator model, designed with space-related components, meets all the requirements to operate a complex legged system.

Foot and Lower Leg

The foot is one of the most important components of a walking and climbing robot. It is expected to provide reliable ground contact, has to absorb shocks to protect the robot as well as the rest of its extremities, it must be lightweight, it has to adapt to the surface, and gather as much information on the ground as possible [17, 18].
Therefore, the foot (see **figure 4**) is specified with an intelligent sensor processing unit including an integrated accelerometer and pressure as well as temperature sensors. The mechanical specification includes lightweight construction and a spring damper system with a deflection of 40 mm. A deflection of this magnitude must be measured because it significantly influences the kinematics of the robot. Therefore, an optical navigation sensor was embedded into the damper housing on top of the damper piston. Since the robots design is aimed at space applications, no cables were allowed to run outside the construction, so a cable channel in form of a cylindrical shaft had to be designed. It also stabilizes the damper piston with the foot attached to its bottom.
At the top of the lower leg, an electronics compartment is placed which also serves as the hardware link between shank and thigh. The compartment contains three stacked PCBs smaller than 32 mm x 43 mm. One is responsible for power conversion from 48 Volts down to 3.3 Volts, the second contains ADC channels and a motor driver H-bridge, and the most important third PCB holds a Spartan 3a FPGA with 1000 kGates to control all attached sensors and to provide the same communication protocol as the joints and main computer.
The optical linear sensor on top of the damper piston scans the inner damper housing surface like a regular optical PC mouse. It provides relative X and Y information while the X information is negligible. Y, however, can be directly integrated and recalculated into the millimeter deflection. Further down at the bottom of the lower leg, the foot with four claws and a rotary protection is mounted. It has three claws at the front and one at the back of the foot. At its center, a PCB cast into polyurethane is integrated which holds an accelerometer, a pressure sensor directly at the center, and two temperature sensors. The sensors are used to gather simple information like ground contact, foot pressure, and slip detection as well as more complex information like surface characterization which is currently not calculated in real-time.

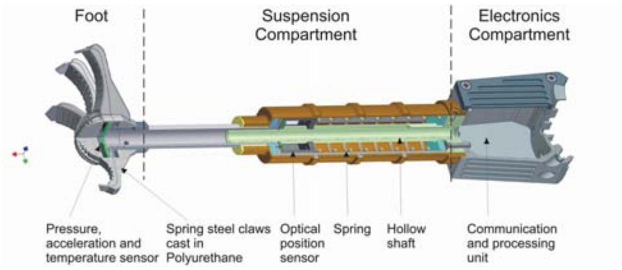

Figure 4: Labeled CAD drawing of the lower leg with foot

SpaceClimber Integration Study

The integration study of the SpaceClimber, shown in **figure 5**, is a breadboard system to test the functionality of the overall actuating system. To build up the legs for the SpaceClimber integration study, 24 of the actuators, six lower legs with foot, and six of the limbs to connect the two last joints of a leg were manufactured and integrated. For shielding purposes, the cabling for power supply and communication with the actuators and the foot is routed within the structure through the hollow shafts of the actuators. The loom involves two cables for power supply and eight for four LVDS communication channels. The body, in its preliminary version, is a lightweight frame structure built of hollow aluminum profiles with a box for the central electronics housing mounted in its middle. The dimensions were selected according to the determined morphology. The first joint of each leg is directly connected to the body.
The electronics mounted in the central body compartment involves the storage batterie packages, a voltage converter board for 5 V and 12 V components, and the central control unit. The central control unit is a custom-designed PCB equipped with an MPC565 Microkontroller. An FPGA connected to the memory bus of the MPC565 is responsible for handling the communication with the legs via the designated LVDS channels. Thus, the MPC565 just has to access memory registers to communicate with the peripherals without the need to handle the whole communication protocol. This way, each leg can be provided with an own communication interface in order to allow high data transfer rates. In addition, a lot of resources can be saved on the microcontroller side. An ethernet interface connected to a wireless communication module is used for the communication with the operator control unit.

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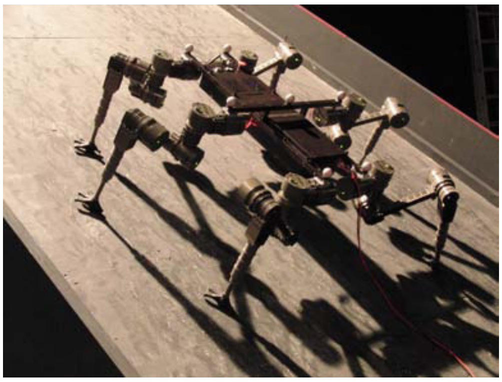

Figure 5: Picture of the fully functional SpaceClimber integration study in a test ramp with 25° inclination

Table 1 gives an overview of the system's specification.

Length (normal posture)	820 mm
Width (normal posture)	1000 mm
Height (normal posture)	2200 mm
Weight	18,5 Kg
Power Supply	44.4 V 4 Ah (Lithium Polymer)
Power Consumption Laid down Standing Walking (average)	 38.4 W 45 W 72 W
Maximum Speed Forward/backward Left/right Turning	 125 mm/sec 50 mm/sec 7°/sec
Maximum Stepsize Forward/backward Left/right	 250 mm 100 mm
Maximum Turning angle per step	 15°

Table 1: Specification of the SpaceClimber integration study

4 Locomotion Control Approach

Controlling the locomotion of a system with 24 degrees of freedom is a complex task. To generate an adequate motion, all joints have to be controlled simultaneously. In addition, a real-time control is absolutely essential to enable fast reactions on disturbances and irregularities. To make this possible, we focused on the implementation of a decentralized control where each component, e.g joints and feet, provides its own intelligence. This way, a high parallelization can be achieved and the calculation costs are distributed over several intelligent nodes.
However, a central controller which has an overview of the whole system has to coordinate and command all the subsystems to achieve a synchronized locomotion behavior.
The biologically-inspired control approach developed to actuate the complex locomotor system of the SpaceClimber utilizes a composition of postural behaviors, central pattern generators (CPGs), and reflexes. Postural behaviors are responsible for keeping the basic posture of the robot and offer other behaviors the ability to translate or rotate the body. CPGs generate the rhythmic motions and handle the coordination of the legs while walking. To react on disturbances, reflexes are permanently analyzing the sensor information and exert influence on the locomotor system if an irregularity has been detected. To provide the ability of quasi-parallel real-time execution and intercommunication of these processes, the behavior-based microkernel MONSTER [19] was used for the implementation.
All advantages of legged robots, such as the ability to shift the center of mass and to walk omnidirectionally, are implemented in this architecture. The following paragraphs will give a detailed description of the main components of the central controller.

Hardware Layer
The hardware layer serves as interface to the subsystems and can be explained briefly. The joints act as actuators and sensors. Other behaviors or drivers can connect to them to write desired position and speed values and to read the actual position, speed, and torque (rather current). The feet deliver information about the immersion of the spring-damped lower leg as well as the pressure measured by the sensor mounted in the sole of the foot and its acceleration on all three axes. An inertial-measurement-unit provides information about the orientation of the system.

Kinematic Driver
The kinematic driver is used to control the position of the feet in a three-dimensional space. Its function is to calculate the desired angles of all joints of a leg to position the foot to the defined point $P_{leg}(x_{leg}, y_{leg}, z_{leg})$ in a coordinate system which has the intersection between the rotational axes of the first and second joint close to the body as point of origin. The first joint of a leg which is directly connected to the body allows to control the angle of attack of the foot around the pitch axis (α_{leg}) while keeping the foot at the defined position. Thus, the leg can be turned to stay in line with the vector of gravity in an inclination. Furthermore, it is necessary to be able to turn the foot around the center of the robot. Therefore, the angles $roll_{leg}$, $pitch_{leg}$, and yaw_{leg} are defined.
In summary, there are seven values per leg which can be set (x_{leg}, y_{leg}, z_{leg}, α_{leg}, $roll_{leg}$, $pitch_{leg}$, yaw_{leg}).

Posture Control
The posture control behavior connects to the kinematic driver to write the desired foot positions for the basic posture of the robot. Other behaviors can command values for shifting (x_{body}, y_{body}, z_{body}) and rotating ($roll_{body}$, $pitch_{body}$, yaw_{body}) the body around its center. The posture driver writes the corresponding desired values for each

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leg to the kinematic driver. All feet keep the same distance to each other while moving the body according to the given values. This behavior is a major feature to enable shifting of the center of mass (CoM) of the system or to rotate the body to stay parallel to the ground. Other behaviors which will e.g. take care that the CoM stays inside the support polygon will write directly to this behavior.

Central Pattern Generator

The Central Pattern Generator (CPG) is the unit which generates the rhythmic walking motions and controls the coordination for all legs. For each leg, a state machine shown in **figure 6** is implemented.

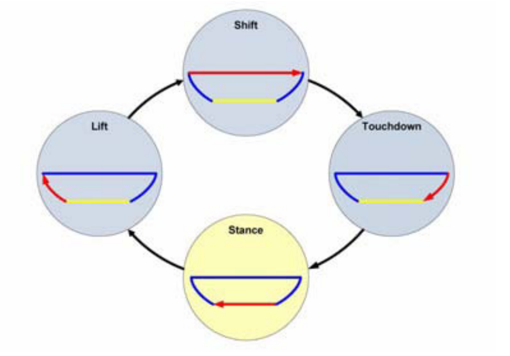

Figure 6: State machine of the pattern generator. The yellow state generates the stance-phase, the three blue states together generate the swing-phase.

The walking motion of a leg is commonly separated into a stance- and swing-phase. During the stance-phase, the leg is supporting and pushing the body into the desired walking direction. In the swing-phase, the foot is lifted off the ground and moved to the new starting position of the next stance phase where it regains ground contact.

The parameters which could be set by other behaviors to modify the walking pattern are the time available for one step cycle of a leg ($cycle\_time$) in milliseconds, the distance the robot should walk in x (x_{amp}) and y (y_{amp}) direction during one step cycle in millimeter as well as the angle it should turn around its yaw-axis ($turn_{amp}$) within this time in degrees. The three parameters $lift\_time$, $shift\_time$, and $touchdown\_time$ define the time available for the different states of the swing phase. All these parameters are the same for all legs. The parameter $phase\_shift$ defines the displacement between the swing-phases of the legs. It can have any value between 0 and 1. A value of 0 will result in a tripod gait where three legs are performing the swing phase at the same time. If the parameter is set to 1, the displacement of the swing phases of all legs is equal. The parameter z_amp which defines the step height in the swing-phase is individual for each leg.

To achieve the desired motions of the legs, the CPG writes to the kinematic driver. Thus, the CPG is writing offsets to the desired values of the posture control behavior.

Reflexes

To guarantee the stability of the robot while walking, especially on steep slopes, it needs to keep its balance. However, tilting of the body has already large effects on desired locomotion on planar surfaces. To achieve stability, the two necessary components for the balance behavior planned for the locomotion architecture were implemented.

A support polygon is the convex hull of all points from one object with ground contact. In the static case, a system is stable as long as the center of mass (CoM) is within the support polygon. Generally, the term "Center of Mass" is used to represent one unique point, the barycenter, of one or more objects. Thus, the best way to keep the system's balance is to shift the CoM of the system over the center of the support polygon. But this is only effective if the system is moving on a flat ground without inclination. If the robot is climbing in a slope, the center of mass has to be projected onto the vector of gravity (see **fig. 7**).

Based on the foot sensor measurements, it is possible to decide whether a foot has ground contact or not. The actual position of all feet can be calculated via direct kinematics. Using this information, a convex hull of foot points with ground contact can be calculated to form the support polygon of the robot.

Knowing both the center of the support polygon and the center of mass, it is possible to move the CoM close to the polygon center to keep the system stable. Within this permanent reflex, one PI controller for each axis (x and y) is responsible to continuously shift the center of mass close to the center of the support polygon.

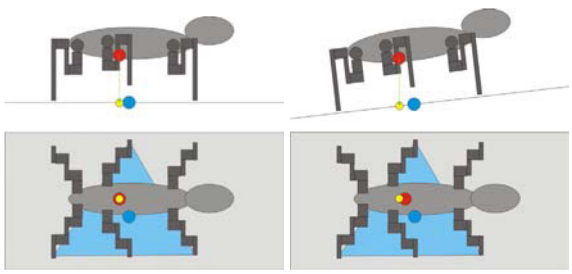

Figure 7: Center of Mass: red point, center of mass projected on the gravity vector: yellow point, center of support polygon: blue point; Left: walking on flat surface, Right: walking on a slope

In the following **figures 8** and **9**, the differences between an active continuously shifting and no shifting can be seen. While shifting the CoM, a more stable locomotion pattern can be observed. If this reflex is not activated it can be seen that the value for the yaw-angle is significantly higher (see fig. 8). According to the lean-movements in y-direction during the activated reflex (which can be seen in fig. 9 on the left side), one can see that the roll angle is more balanced in both directions. The walked distance in x-direction is nearly equal, with a small advantage for the active continuous shifting. Also, it could be observed that

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the robots rear buckles a little if the reflex is turned off.

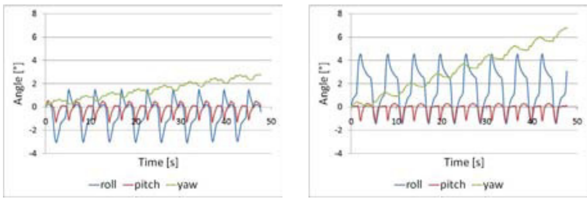

Figure 8: Roll, pitch and yaw angles during walking with activated and deactivated stability reflex

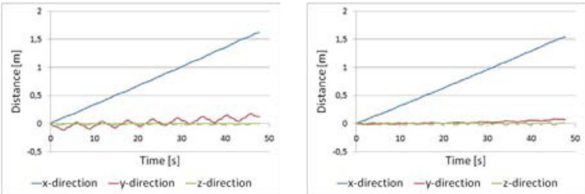

Figure 9: Bodyposition in global coordinates during walking with activated and deactivated stability reflex

5 Experiments

In an experiment the energy efficiency of the SpaceClimber robot was evaluated. Therefore, the system had to walk on flat ground and on a slope with 25° inclination while the power consumption was measured. Two different gaits i.e. walking with just one leg in swing phase at a time and the tripod gait, were tested. **Fig. 10** shows the power consumption of the SpaceClimber at the different setups.

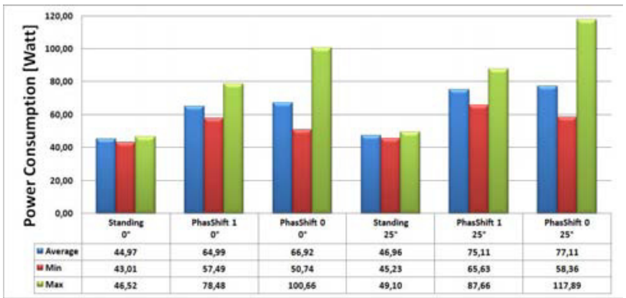

Figure 10: Power consumption of the SpaceClimber integration study with varying inclinations and walking gaits

The basic power consumption of the system with inactive motors is 38.4 W. As can be seen, the additional energy required to hold the basic posture on flat ground by actuating all 24 motors is $\sim 6.6\,W$. In 25° inclination with $\sim 47\,W$ it is merely 2 W higher than on flat ground. While walking with the uniformly distributed gait on a horizontal plane, the power consumption with $65\,W$ is approximately 2 W less than with the tripod gait. Also, in the slope with 25° inclination, the average energy consumption is $\sim 2\,W$ higher with the tripod than with the other gait with 75 W. On average, only a $\sim 10\,W$ higher power consumption is needed for walking in the slope.

Regardless of the inclination, the uniformly distributed gait has least power consumption. Compared with the energy-efficiency of the formerly developed walking robots, these results are very satisfactory.

6 Summary and Outlook

In the course of the development of the SpaceClimber robot, various important parts of the system were designed from scratch: The energy-efficient joints including all necessary electronics for control, state observation, and communication, provide high torques and speeds at a very low weight. Sensor data-collecting feet were developed which have a very high integration density compared to existing solutions providing the possibility for further work in the field of surface characterization and classification. The overall weight of the robot with 18.5 kg is very low as is the power consumption with around 45 W while standing.

In a further step, to arrive at the final prototype, we will concentrate on the central body design and the development of a sensor head for visual perception of the environment. The sensor head will be equipped with a laser scanner and an additional pair of cameras for stereo vision. It is planned to use the information from these sensors to detect the most promising surface areas in order to plan the foot placement for the next steps. The weight and dimensions of all electronic components within the corpus will be reduced to allow a small and lightweight design for the prototype. A six axis force-torque-sensor will serve as mounting point at the body for each leg. The measured values will be used to implement an impedance control for each leg to increase the robustness of the system. The energy consumption was measured without the permanent reflexes. Due to a better load distribution, a decreased maximum energy consumption could be possible. Because the development of the scientific payload is not part of this project, the GIPF [20] which combines the most important instruments for in-situ investigation, was selected as a reference. The dimensions of this component are 50 mm x 68 mm x 147 mm and the overall weight is 800 g. By attaching it to the bottom side of the body it will be possible to place the instruments in front of a sample with high precision.

7 Acknowledgements

The authors would like to thank the SpaceClimber team and all supporting staff at the DFKI Robotic Innovation Center Bremen. The project SpaceClimber is funded by the German Space Agency (DLR, Grant number: 50RA0705) and the European Space Agency (ESA, Contract no.: 18166/04/NL/PA).

ISBN 978-3-8007-3273-9

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ISBN 978-3-8007-3273-9