Towards an Intelligent Foot for Walking and Climbing Robots.

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Abstract

Technical locomotion has up to now been dominated by wheeled or later on tracked approaches. These locomotion principles may be implemented in a straight-forward fashion and are a robust way to move. However, wheels quite soon reach their limit in negotiating rough ground and even tracks can't cope with all kinds of terrain. At least when it comes to climbing vertical surfaces, for example canyons on Mars or the interior of volcanic and lunar craters wheels and tracks are no option for locomotion. The intelligent foot prototype with embedded sensors that is presented in this paper is part of the SpaceClimber project[1], which aims at a six-legged climbing robot for steep and rough terrain, [1]. The robot is meant to be used for planetary exploration missions such as lunar crater exploration and sample return missions.

1 Introduction

Walking robots make use of a locomotion principle which evolved in nature millions of years ago. Legged locomotion is flexible and provides high mobility. However robots with legs can be endangered by failures such as stumbling or slipping and even falling. Biological systems make use of reflexes to react to external disturbances and master difficult situations. Furthermore sophisticated sensory input can prevent biological systems from even having the need to trigger a reflex.

Especially in biped robots reflexes for tripping and slipping are an important issue. Tripping or stumbling in a biped robot can cause system failure and even serious system damage. In quadrupeds, six- and more-legged robots, stumbling as well as slipping are no immediate sources of damage, since the risk of falling over is lower. However, with slipping and tripping the efficiency of locomotion is affected in any case. Boone and Hodgins investigate slipping and tripping reflexes for biped locomotion for example in [2]. They argue that locomotion in rough terrain requires the robot to react to unexpected irregularities in the ground *after* making contact with the ground. Reactions often have to be executed quickly, without explicit modeling of the exact nature of the ground and with limited sensory input, thus a reflex is triggered.

Also robots with more than two legs need reflexes in order to maneuver safe and efficient in rough terrain. Espenschied et al. [3] present a hexapod robot with biological inspired reflexes. The implemented reflexes include a *Stepping Reflex* and a *Swaying Reflex*: As long as there are only small horizontal forces acting on the robot, the robot counteracts by adapting the compliance of the leg. If the force/displacement overcomes a certain threshold, the stepping reflex becomes active: The robot moves its foot position in order to improve the robot's support.

The so called *Elevator Reflex* becomes active whenever a leg in swing phase collides with an object. In this case, the leg is retracted a bit and then lifted higher in order to step onto or over the object. If the robot does not encounter ground contact when expected, a *Search Behavior* becomes active. This more complex reflex starts to move the foot in circles with increasing radius for a certain time in order to find a satisfactory foothold.

For more than 20 years researchers are investigating the estimation of the ground a legged robot is walking on. Already in the 1980s Sinha and Bajcsy started research on surface exploration through legged robots, [4]. They proposed a methodology called *Active Perceptual Scheme (APS)*, [5] giving a robot the possibility to make estimations of ground properties while walking. They define several *Exploratory Procedures*, which are used to identify the parameters *penetrability*, *compliance* and *surface roughness* (slippage).

For sensing Sinha and Bajcsy used a wrist force/torque sensor with six axes. However, they only implemented their approach on a foot mounted on an industrial robotic arm (Unimation PUMA 560), there is no literature available where they tested their approach on a real walking machine.

Bicci et al. proposed a similar approach, [6] using *Exploratory Subroutines* to extract ground parameters. To gain information on the ground they make use of a six axis force/torque (F/T) sensor in the ankle. A six axis F/T sensor should be able to provide full information on the intensity and direction of ground interaction forces. This includes the friction force by which the danger of slippage can be assessed.

More recently (2003) Tokuda et al. proposed an ankle-foot mechanism with two passive degrees of freedom (DOF),

[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)

[7], respectively two active DOF, [8] to estimate the robustness and shape of the ground. They use a method called *Center of Force (COF)* to draw conclusions on the character of the ground the robot is walking on. Their thesis is that the COF changes during the step, if the foot is on a rough ground (a sharp point touching only a fraction of the foot), whereas the COF is constant on a flat one.
In subsumption of the above mentioned topics,

> "*[...] the approximate nature of sensor information obtained at a distance means that it is not always possible to sense the surface properties of terrain before making contact*", [2].

Thus a need for an "intelligent foot" arises. In this context intelligent means that the foot is able to preprocess sensor data in order to reduce communication load and to relief the high-level controller from computational tasks. The foot can be seen as a subsystem of the walking machine and should be as self-contained as possible in terms of sensing, sensor processing and ground properties assessment. This subsystem should enable the robot to draw conclusions on the properties of the ground it is walking on.
Eventually the subsystem developed in this work will follow an idea, formulated already in 1990 by Krotkov:

> "*A legged robot can supplement image information with contact information. It can treat every step as an experiment, much as the blind person uses a cane to learn about the world*", [9].

In the following section different experiences concerning the feet of walking robots at the authors' institute are presented as preliminary work. The current design of an intelligent foot prototype for the SpaceClimber robot is presented in section 3. In section 4 some experiments concerning surface assessment and slip detection are presented. Section 5 presents the conclusion and gives an outlook on the next iteration of developing an intelligent foot for the SpaceClimber robot.

2 Recent Foot Development at DFKI

In this chapter different feet previously used for walking robots at our institute are presented. They range from simple rubber feet over magnetic feet to feet with claws for manipulation and locomotion.

Scorpion
The Scorpion robot, **figure 1**, is an eight legged walking robot, [10]. Each leg has three active and one passive DOF, resulting in a total of 32 DOF (24 active and 8 passive). The biomimetic control design allows for flexible walking behaviors in various terrains. The basis of the walking patterns is a result from research of walking patterns of real scorpions.

For adaption to the terrain various reflexes have been implemented. These include a hole/ridge reflex, stumbling correction and a lean behavior. For triggering reflexes proprioceptive data is used. The passive DOF of a leg provided by a suspension in the lower leg is used for passive ground adaption. The deflection of the spring is measured using a linear potentiometer. Other proprioceptive data incorporated into the reflexes are the currents of the active DOFs of each leg and the actual tilt angle of the robot, measured by an IMU.

Figure 1: Scorpion robot and some experimental feet

The basic feet of the Scorpion are very simple rubber feet made of door stoppers. There are no sensors attached directly to the feet. All information on the ground is measured indirectly from proprioceptive data such as currents or the deflection of the spring in the passive DOF of a leg. The information of the linear sensor however is quite poor. The data is very noisy, it should only be used for a binary decision: Ground contact true or false. An advanced load balancing between the legs is not possible.
Experiments have been conducted in order to improve the mobility of the robot in steep slopes by new foot designs. In these experiments the slippage of different feet in an artificial crater environment has been evaluated, [11]. Section 4 gives some more information on the experiments.
All different feet prototypes are made of polyurethane in a casting process. The idea behind this process is to be able to cast certain sensors directly into the foot structure. Another advantage is that the Shore hardness of the feet can be tuned during the casting process, also a wide variety of shapes for the feet are possible. Figure 1 (right) shows two different types of feet evaluated on the Scorpion robot. The feet have a big contact area in order to avoid sinkage in loose gravel. Unfortunately the last segment of the Scorpion's legs can rotate freely, so that each foot that has a certain minimum diameter acts as a wheel in a slope: The robot tends to roll down the hill. Another disadvantage of free rotating feet is that twisting of sensor cables between foot and leg can not be controlled, secure cable connections can not be guaranteed.
From the experiences with the Scorpion the following conclusions for the design of an intelligent foot can be drawn:

- It is possible to implement basic reflexes with proprioceptive data but for detailed information about the substrate, sensors directly placed into the feet are necessary

- Sensors in the foot require cabling, in order to protect the cables from excessive twisting, a free rotation of the foot with respect to the leg has to be inhibited

- Free rotation also effects the stability of locomotion in steep slopes

Scarabaeus

Scarabaeus [12] is a six legged robot with three actuated degrees of freedom per leg, **figure 2**. A fourth actuator integrated in the lower leg is responsible for opening and closing a grabbing device attached to the end of the lateral segment. The gripper consists of three claws which are actuated by a worm drive. These elements were developed to perform two functions: It is intended to avoid sinking into dusty surfaces by spreading the claws to enlarge the contact area. At the same time the device provides the capability to use the legs as manipulators. To detect whether a claw has contact with an object or not, each claw finger is equipped with a piezo-electric load cell providing information about the gradient of the force applied to the material.

Figure 2: Scarabaeus with feet enabling sampling

A spring, which is integrated into the lower leg, is used to absorb shocks while walking and to counteract tensions between the legs. A linear potentiometer is included to the spring-damped distal segment to measure its compression which indicates the bearing pressure and is used to sense ground contact.

Aramies

The feet of the four legged robot ARAMIES [13] were developed to offer hold in steep inclination by the use of actuated claws in order to cling to solid structures in rock faces, **figure 3**. The sole of foot has a dimension of 18 cm x 12 cm (L x W) with outstretched claws. Thereby it provides a big area of contact to avoid sinking into deformable surfaces and attains a higher lateral stability to the overall system. The three claws are interconnected and can be actuated up and down with one active degree of freedom. This enables the system to cling to the surface or to roll over the ball of the foot. To detect ground contact pressure sensors are mounted on the bottom-side of each claw, the heel and the ball of the foot. The sensors are covered with shock absorbing rubber plates to prevent mechanical damages due to penetration of surface material and to increase the friction. In addition an infrared sensor positioned in the middle of the footprint is used to measure the distance between foot and ground level. By use of this sensor it is possible to decrease the downward speed of the foot at the end of the swing-phase before it impacts to the ground to reduce mechanical stress on the leg.

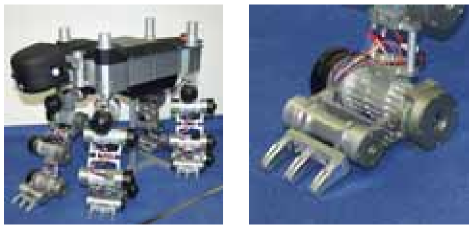


Figure 3: Aramies robot and foot with actuated claw

The ARAMIES prototype demonstrated its climbing capability obtained by the feet design in an experiment were the system was able to climb up and down in a rung wall with an inclination of 70°.

LittleApe

The LittleApe robot, [14] is a four legged robot build after the antetype of a chimpanzee (*Pan troglodytes*) and its close relative, the bonobo (*Pan paniscus*), see **figure 4**. LittleApe has 14 active DOF, three for each leg and one to actuate each rear foot. The feet on this robot serve different applications. The robot should be able to walk on two and on four legs and should also be able to climb. For the feet development this requirements had to be taken into account. Chimpanzees, bonobos, and other primates show a special locomotion behavior called knuckle walking. Here, weight is supported not by the complete hand, but only by the dorsal side of the middle phalanges. While walking, due to muscle activity, the hand and wrist configuration is quite rigid. The fingers are positioned in a very compact way and special fat pads on the phalanges provide further bearing and damping. As a result, the fragile fingers are protected optimally and can be used to manipulate when not used for locomotion.

Figure 4: LittleApe and its feet

The biological model provides several features, including climbing movements. The rear feet of LittleApe base on a 3 mm thin and 100 mm long Polyoxymethylene (POM) plate including a hook in the front. With a length of 100 mm the foot fits into the normalized and rounded segment proportions copied from chimpanzees. The hook is an abstraction of the prehensility and can be used for climbing in defined areas like fences or step ladders. The front of the feet can be actuated up and down, each with a range of about 70 degrees. A passive DOF is added to balance irregularities on the ground. The range of motion is limited by the structure to 10 degrees. Two force sensors are applied in the front and two in the rear of each foot (in each case one on top, one on the bottom). With the received sensor data it is possible to detect a touch down, measure the applied force, evaluate the torque at each time of the step cycle, as well as calculate the center of mass of the robot. In addition a load distribution can be made, in order to avoid a lateral tilting of the robot.

Pithekos

Pithekos is a four-legged robot with flexible feet allowing dynamic walking, **figure 5**. The robot has eight active DOFs, two in each leg. The weight of the robot is about 2 kg and the dimensions are 490 mm x 84 mm x 207 mm (L x W x H). The feet of this robot consist of Makrolon[2]. Using the flexible characteristics of this material, the robot is able to run stable with a dynamic walking pattern.

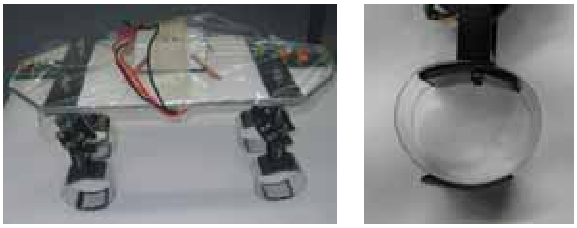


Figure 5: Dynamic walker Pithekos and its feet

The material is formed into a circle and attached to the lower leg. The part of the foot which has ground contact is covered with a corrugated material to increase friction during stance phase. The standard locomotion pattern of the robot is a trot gait, meaning that front and rear legs are moved simultaneously. During each touch down phase, the foot becomes compressed and acts like a spring, storing the kinetic energy as potential energy. The initial tension and release of stored energy during the take off movement supports the movement of the robot. Depending on the angle of attack, this can be used to move forward or to jump in one place. Using the angle of attack in a proper way the robot is able to run with a speed of 70 cm/s (1.42 body lengths per second), this walking pattern includes a flight phase, where no leg has ground contact. The ground clearance during the swing phase is about 2 cm to 3 cm. Walking curves with a minimum diameter of 34 cm is possible with this robot.

Different materials with an equal spring rate while bend can be used for the robot, including spring steel. The experiences from Pithekos show that proper design of the feet can enable locomotion principles that would otherwise not be possible on the same robot.

[2]Makrolon is a registered trademark of the Bayer group

Asguard

The Asguard robot is different to most walking machines that have been developed so far. The legs are mounted on wheels, see **figure 6**. Due to this, the robot is able to walk fast (2 m/s about 2.1 body lengths per second) in flat and unstructured terrain, [15]. Obstacles like stairs can be overcome quite easily, caused to the space between two legs each of which delivers a contact surface allowing the robot to push itself upwards on the stair or obstacle.

Figure 6: Asguard and compliant legged wheel

POM is used as material for the legs. The material structure itself is quite thin to allow deformations and represents the main elasticity in the system. During the ground contact the structural shape of the legs can absorb shocks and store the energy. Attached to each leg are the feet. The feet consist of 2 mm thick rubber with shore 50A and are itself (caused to a total deformation during touch down) too flexible to store energy. Nevertheless, the material still absorb shocks and is important to increase the contact surface and thereby the traction on the ground.

Magnet-Crawler

The Magnet-Crawler, see **figure 7**, uses the same leg principle like the above mentioned Asguard robot, but in a smaller scale. The weight of this robot is about 650 g. Different to the Asguard robot is the implementation of permanent magnets in each foot. For each foot eight magnets in two rows are applied. Through incorporating the magnets, the feet are loosing the damping capability but allow the robot to climb on vertical surfaces, given that they consist of a magnetic material. Thanks to the compliant feet, the magnets are automatically arranged to the wall optimally and can be detached easily during movement of the legged wheel. Like in Asguard, no sensors are applied directly to the feet.

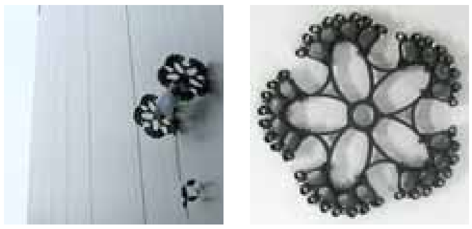


Figure 7: Magnet-Crawler and magnetic legged wheel

3 Lower Leg Design for SpaceClimber

In this section we present the first prototype of an intelligent foot subsystem for walking and climbing robots. In this case the foot is part of the SpaceClimber robot. SpaceClimber is a six-legged walking machine for steep slopes and very difficult terrain as can be typically found in lunar or martian craters. The foot is intended to enable both, safe locomotion and assessment of the current ground properties. The whole design is oriented to a device that provides stable foothold in various situations and under difficult surface conditions. In the next subsection, the mechanical design is presented, after that the electronic layout containing VHDL design and sensors is discussed.

Hardware Design

The mechanical design of the foot includes also the whole lower leg, thus all components from the last joint of a leg down to the ground are considered in the term "intelligent foot". This is due to the suspension that directly effects the ground contact of the foot. Another reason for extending the term foot to the whole lower leg are space considerations. The foot itself does not provide enough space to incorporate the electronics needed for sensor processing and power supply. The foot / lower leg subsystem presented here is developed to enable the SpaceClimber to climb in crater slopes of up to $40°$ covered with loose sand, gravel and small rocks. The first prototype of the "intelligent foot" is depicted in **figure 8**.

To generate enhanced foothold with each step, the foot is equipped with extending claws. Since climbing up is more difficult than climbing downhill, we designed the foot with three front claws and one claw at the ankle. The middle of the foot provides enough space for a sensor board. The skeletal structure is casted into a flexible polyurethane hull to be able to adapt to small irregularities of the ground. Additionally, the deformation of the flexible hull can be measured and thus the contact force of the foot with the ground can be estimated, see also section 4. Further sensors placed directly into the foot include an accelerometer and a temperature sensor.

Since SpaceClimber is envisioned for usage in space applications all cabling has to be routed inside the structure. To protect the wires lead through the lower leg from interfering with the spring in the *Suspension Compartment*, a central guiding shaft is used. The piston attached to the foot is also guided by this structure. From the experiences with Scorpion we designed a rotary protection inside the suspension compartment in order to inhibit free rotation of the leg. The displacement of the piston is measured with an optical linear sensor.

The whole electronics for energy distribution, collection of sensor signals and communication with the central processor are mounted in the *Electronic Compartment*. The processing unit for the foot is a Xilinx FPGA. All logic that is needed for sensor readout and communication with the robot's central processor is implemented in the FPGA.

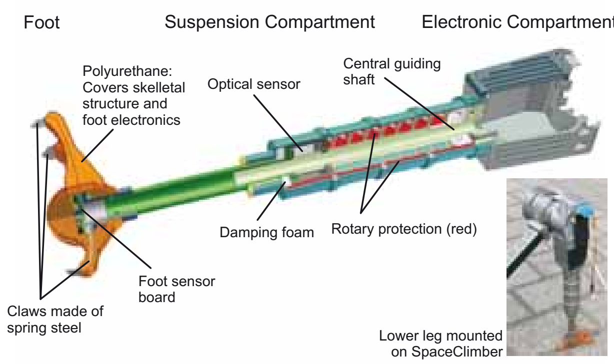


Figure 8: Description of SpaceClimber's lower leg. Bottom right displays the leg mounted on the robot, visible cables are due to experimental data logging with external PC.

Electronic Design

As described above, the electronics compartment contains a PCB stack with a powerful FPGA. The FPGA is used to configure, sample and (pre)process sensor values. The deployed FPGA is a Xilinx Spartan 3a with 1200$\hat{k}$Gates and provides enough slices for the sensor driver modules and post processing of sensor data. Mounted in the suspension compartment is a small PCB with an optical sensor for measuring the spring deflection. Embedded in the foot itself is an electronic board carrying a pressure sensor with embedded temperature sensor, an accelerometer and an additional temperature sensor. From the pressure sensor ground contact as well as contact forces can be calculated, the accelerometer is used for slip detection, while the temperature sensor is used for calibrating the pressure sensor. Additionally the temperature could be used to build up temperature maps and for substrate discernment.

Software Design

The FPGA-Code mainly consists of three layers, as depicted in **figure 9**: The lowest layer serves for sensor read out. The sensor controller contains four modules to configure and control different sensors. A pressure sensor combined with the first temperature sensor, an accelerometer, a linear displacement sensor and a second temperature sensor. The advantage of VHDL hardware descriptions synthesized to run on an FPGA is that every module runs truly parallel at the same time. Therefore all modules produce data at the same time enabling the collection of data of different sensor modalities from one time instant.

The middle layer consists of a sensor collector which gathers the sensor information and converts them into SI-units. This improves the readabilty of log files. Additionally, but not yet implemented, there may be a layer which provides further calculation capabilities such as for example an FFTmodule, a Kalman filter-module and others in order to advance in the direction of processing more information directly in the foot.

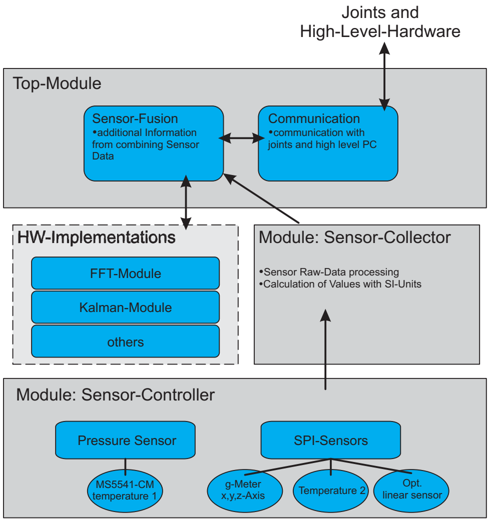


Figure 9: Layout of FPGA hardware design.

The top module contains a sensor fusion module. By combining information from the linear sensor and the pressure sensor, different states of the lower leg can be identified. For example a boolean touchdown flag can be set. The pressure sensor is also used to correct drifting values from the incremental linear sensor with each step, i.e. resetting it to zero while the foot is in the air.

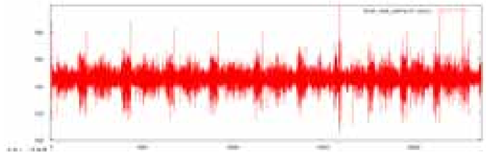
4 Experiments

In this section preliminary experiments with Scorpion and Scarabaeus concerning slip detection as well as experiments with the first prototype of SpaceClimber's intelligent foot are presented.

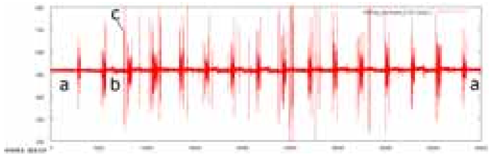
Slip Detection on Scorpion and Scarabaeus

Both, Scorpion and Scarabaeus, are walking robots with small rubber feet. These rubber knobs do not contain any sensors so that for conducting experiments accelerometers were glued externally. During the very first experiment the accelerometer was attached to the lower legs damper housing instead of the foot which lead to unusable sensor readings. Even the slightest body movement was visible on the diagram (see **figure 10a**).

The solution to this shortcoming was to attach a free wired accelerometer-chip directly onto one of the feet. It is placed off the geometric center of the foot which is rotatable. Caution had to be taken so that wires from the sensor to the measuring device do not tear off. The results can be seen in **figure 10b**. This diagram shows only real foot movement without the necessity for advanced filtering techniques.



(a) Leg mounted accelerometer



(b) Foot mounted accelerometer

Figure 10: Acceleration data during slip experiments

The markers (a) represent the ground noise level while the robot is not moving at all. (b) shows movement of the robots body. In this case it was a change in the robots body orientation. Greater body rotations cause a change in attitude of the feet which can be measured. The most interesting part of the sensor data diagram is at the position of marker (c). It shows a spike with minimal length caused by the slipping foot. This is caused by rising body tension during the support phase while the robot is walking. Lifting another foot causes a change in body balance and weight distribution and leads to additional load to the feet in stance phase. The tension is then unloaded by very sharp and strong foot movements. The spike of interest with high amplitude is therefore usually surrounded by periods of no movement.

From the reference measurement as shown in figure 10b it was possible to develop a simple algorithm that detects this kind of spike in realtime even on small processors. The so called SlipDetector was implemented on a windows machine and also for a MPC565 32 bit micro controller executing the operating system of the robot (MONSTER, [16]).

The information of a slipping foot is used to slow down the robot, to stop it completely or to correct its posture according to the amount of slippage the feet experienced. If slippage decreases during the next couple of steps the walking speed is slowly set back to normal. This acts as an active kind of surface dependent speed controller. Like a car on snow or ice full speed or slowest speed is not the best choice to overcome failing locomotion. A certain percentage of slippage during locomotion results in the fastest movement.

Surface Discernment with SpaceClimber's Foot

During the development phase of the current foot design, experiments were conducted to create a substrate classification method that applies known machine learning algorithms to the sensor data. The experiments are conducted with the lower leg mounted to a linear actuator. The linear actuator moves the lower leg prototype vertically using a sawtooth profile to contact the foot with the underlying surface. Data from accelerometer, pressure sensor and optical linear sensor are collected. The conducted experimental series comprises over 14000 separate footsteps at several different stepping frequencies. A box of basalt, a three centimeter thick sheet of neoprene and a massive aluminum plate were chosen as substrates. The recorded data sets are analyzed and filtered using MatLab and then fed into the WEKA Toolkit. WEKA uses four different machine learning algorithms (NB, C4.5, SVM, KNN) to calculate the strength and usability of features provided by MatLab.

The process only works with the time of attack through the stance phase until lift-off. This is why all information recorded while the foot was in the air has been automatically deleted before analyzing the data to create classifiable features. Differences between the substrates are noticeable even by the viewers eye and therefore especially by the learning algorithm. During the stance phase on aluminum the foot barely moves. The accelerometer casted into the polyurethane experiences vibration from the linear actuator (or the robot in ”real life” experiments) but since the surface is not deformable or movable these vibrations are reduced to a minimum. Steps in neoprene (a substitution for elastically deformable substrate), however, show very strong vibration because even the whole surrounding of the foot is able to move in every direction. Basalt split instead shows even less vibration than aluminum because the foot formed a little crater into the surface i.e. tightened the surrounding material and the spherical sole digs into the regolith completely. The base plate with the soldered sensors was therefore not able to vibrate anymore because pressure onto the polyurethane sole could not exhaust to any direction.

The result of the classification experiment is that previously trained types of substrates can be classified with very high accuracy. The classification using only statistical features generated from pressure sensor data and accelerometer values both produced results above 95%, **figure 11**. If the algorithm is trained with several different substrates for various walking speeds it will be able to create a fuzzy logic like categorization of the surface resulting from the similarities to one or more known ones.

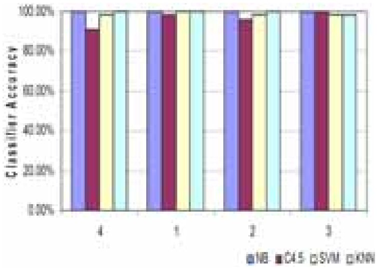


Figure 11: Results of substrate classification using accelerometer (4 = test set, 1-3 training sets)

5 Conclusion and Outlook

In this paper we presented different feet for walking robots. A foot for a walking machine has to be seen in the context the robot should operate in, there is no ”general foot” working for all kind of applications. The recent foot design focussed more on the structure of the foot itself, for example to enable dynamic walking with a robot providing only 2 DOF per leg.
With the application of walking machines in crater environments, such as Scorpion in an artificial lunar crater or the intended use of SpaceClimber for crater exploration, more information of the underlying substrate is desired in order to increase locomotion stability. This is why the SpaceClimber’s feet are equipped with sensors providing information of the current foothold. Experiments for surface discernment have been conducted with a single lower leg prototype in a test bench, yielding promising results for further investigation.

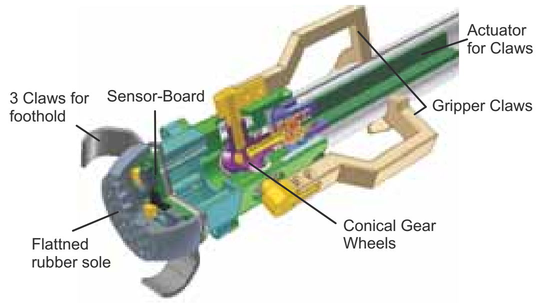


Figure 12: Second prototype of the intelligent SpaceClimber foot

To provide more detailed information on parameters as surface roughness and angle of attack, the claws of the foot are going to be equipped with strain gauges. On the software side, classification methods and additional filters for sensor data preprocessing have to be transferred from WEKA toolkit onto the foot processor. By this real time classification and better reflexes will be enabled.
Additionally to the software work, a second iteration of the intelligent foot hardware is started with the goal to improve certain shortcomings that have been identified. First, the thickness of the sole is reduced in order to gain more meaningful pressure measurements. Second, the sole is flattened with greater diameter to provide a bigger footprint and to free space for four instead of one pressure sensor on the foot’s sensor board. With four sensors a center of force can be calculated and thereby a more precise estimation of angle of attack of foot to ground can be realized. Another goal of the second prototype is to simplify maintenance and assembly of the lower leg.
The main driver for a new iteration was the integration of an active DOF in the foot. An actuator is planned to control claws in the front legs to implement a sampling device, see **figure 12**. However, once a motor is integrated into the lower leg structure, with some modifications it can be used

to rotate the foot. By being able to rotate the foot a better adaption to changing ground characteristics and walking patterns is pursued. This will be implemented in the rear four legs, thus two different kinds of feet are implemented at the SpaceClimber, following the different needs that arise in the usage of the feet.

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