An Approach towards Autonomous Outdoor Walking Robots

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Abstract— **We present six and an eigth-legged walking robots, which are controlled with the same biomimetic ambulation control approach. The goal is to build up real-world capable walking robots. The control of these robots is based on two biological control primitives: Central Pattern Generators and Reflexes. The Central Pattern Generators are controlled from a higher behavioral level by means of Basic Motion Patterns (BMPs) and posture control behaviors (PCBs). With this approach omnidirectional walking and a smooth and fast crossing between different motion patterns is possible. Additionally the posture of the robot can be changed while walking. The robots were successfully tested in rough terrain, with obstacles as high as the robots and different terrains like sand, grass, asphalt and rock piles.**

Keywords— **Biomimetic, Walking Robot, Basic Motion Pattern(BMP), Central Pattern Generator(CPG), Outdoor-Capability.**

I. The SCORPION Robots

The focus in the SCORPION project[1] is the development of an biomimetic eight legged walking robot (fig. 1). Because we think our ambulation control approach is also suitable for the more widely studied hexapods we also built a six-legged robot (fig. 9) which is equipped with the same electronical and mechanical parts as the eight legged robot. The length of the eight-legged robot is 65 cm and the six legged robot is 52 cm long. The other dimensions are shown in figure 2. The weight of the fully equipped robots(including 3.8 Ah batteries, communication equipment and sensors) is 9.8 kg for the six-legged and 12.5 kg for the eight-legged robot.

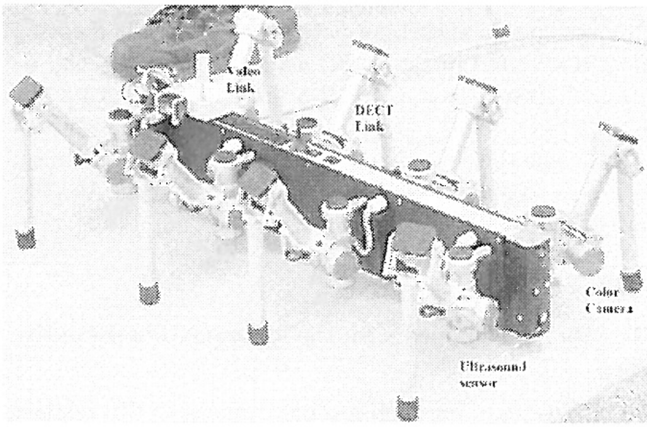

Fig. 1. The SCORPION Robot

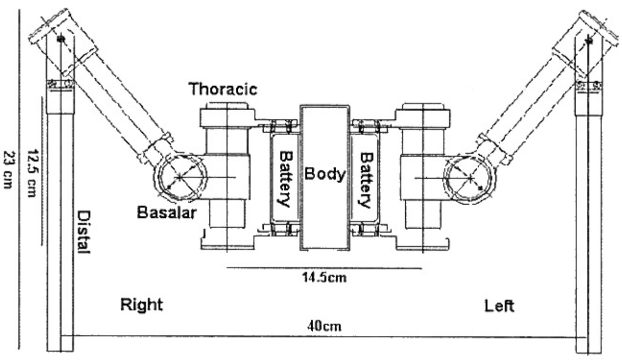

Fig. 2. The mechanical design of the Scorpion legs. This front view of the robot shows left and right side legs with the body in the center. Each leg consists of 3 parts: 1) thoracic joint, 2) basal joint and 3) distal joint.

A. The Leg

The most challenging parts of a walking robot are the legs, which in our vehicle provide 3 degrees of freedom per leg. We feel confident that 3 degrees of freedom is the minimum needed in a flexible outdoor-capable walking robot, for example it provides the possibility to walk omnidirectionally in narrow spaces.

The leg consist of a thoracical joint for protraction and retraction, a basal joint for elevation and depression and a distal joint for extension and flexion of the leg (see also fig. 2). The joints are actuated by 24V, 6Watt DC-Motors with high gear transmission ratio for sufficient lifting capacity.

An important constraint in the development was the capability of operating outdoors. Therefore a good tradeoff between making the leg as light as possible to improve its lifting capacity and shielding it against the environmental influences like dust and water had to be found.

We achieved a weight of 950 gram and a weight to lifting-capacity ratio of 1:8 in a watertight leg design, which is a prerequisite to walk up steep rises or to walk over obstacles as high as the robot itself.

Another challenge was to integrate some compliant elements in the design to achieve sufficient robustness to withstand the mechanical stress in an outdoor terrain. The most important function of these elements is the absorbtion of the high energy shocks when the leg hits the ground,

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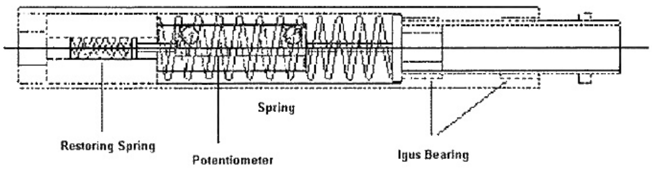


Fig. 3. The distal segment contains a spring damped compliant element with a built in potentiometer to measure contact and load on individual legs.

especially when the robot slips over a rock and a single leg has to sustain the full weight of the robot.
The most energy absorbing part in our design is a spring element integrated in the distal segment of the leg(fig. 3) The distal spring element is also used for measuring the ground contact force by an integrated linear potentiometer. From this the robot can compute the load for each leg, enabling us to make use of the "Early Retraction Acceleration" principle[15].

B. The Sensors

The robot is equipped with the following proprioceptive sensors:

- Motor Encoders for each motor to measure the relative joint angle
- Hall-Effect Motor Current Sensors for each motor
- Analog load/pressure sensor in every foot tip
- Power-Management sensors, providing current battery voltage and current power drain
- three dimensional tilt-sensors (pitch, roll and yaw)

The following exteroceptive sensors are integrated:

- Ultrasound distance sensor for obstacle avoidance
- Compass sensor for heading control
- Pressure sensors in each foot tip used as contact sensors

It is important to note that the leg itself can be used as an exteroceptive sensor. One can use the current sensors of the motors as a tactile sensor during movement, e.g. if the leg moves forward and presses against an obstacle, the current, into the thoracic motor will raise very fast.

C. The Operator / Test-Equipment

In order to allow an operator to communicate with the robot or to take data samples during a test run, the robot is equipped with a wireless 28K Baud bi-directional communication link and a PAL CCD Camera with a 5GHz video/audio link for video transmission. So it is possible to use the robot as a semiautonomous system.
The Operator can control it via high-level commands like "go in direction xyz", "walk forward", "left", "right", "go up", "go down", "move sideward", "turn", etc.. To supervise the system all relevant sensor data is send back from the robot to the operator desk. The operator has the possibility to switch between a video-image from the front camera and an additional tail camera.

D. The Control Hardware

To control the robot a network of Infineon C167 and C164 Microcontroller Derivates are used.
It consists of one Master-Controller(a C167) which handles higher behaviorial control, communication to the operator and data processing of the exterioceptive sensors. The master controller is connected via a CAN-Bus network with the Leg-Controllers (C164). The leg-controller is used for the local control functions (Central Pattern Generator and Local Reflexes), to process the proprioceptive sensors and to drive the DC-Motors. To be able to process the data from the Motor-Encoders fast enough the C164 is supported by an CPLD[2]. In a new version of the hardware we will use a MPC555 for the higher level control and a FPGA for the local control of the legs.

II. The Biomimetic Control Approach

Many approaches to leg based walking already exists [5], [?], [6], [8], [9], [14], most of them biologically inspired.
Our ambulation control approach combines two main biological inspired concepts, the Central Pattern Generator (CPG) and the Reflex. Whereas a Central Pattern Generator is a set of nerve cells which is able to produce rhythmic motion patterns without the need of sensory feedback [7], reflexes relies heavily on the sensor-motor-feedback. It is assumed that CPGs are not learned or adapted by the animal but produce a set of low-level locomotion skills specific for the species. Applied to a robotic system this implies, that it is possible to apriori define a set of Basic Motion Patterns (BMPs), which can be produced without the need of sensory feedback.
A well known reflex based locomotion approach is the "Walk Net"[6], It is based on the assumption that only local sensory feedback at the legs and a coupling between the control of neighbored legs is needed for stable walking. A robot control concept which is based on a CPG model is the ambulation controller[5]. To control the CPGs it uses a command neuron[2] like approach. Here the motions for lateral left, lateral right, forward and backward walking are implemented as finite state machines. The control to execute one of these finite state machines is done by a command neuron like structure.
The ambulation control approach presented here also uses a CPG model, but in contrast to the command neuron approach it uses combinable "Basic Motion Patterns" (BMPs).
By combinable we mean, that firstly it is possible to activate more than one BMP at the same time. Secondly each BMP can be activated with different strength. Thirdly different behaviors can take simultaneously influence on the activation of a BMP. And fourthly the observable movement is the result of overlaying all activated Basic Motion Patterns.
A Basic Motion Pattern(BMP) describes a trajectory of the leg in the joint angle space. For a pure forward movement this means, that the trajectory of the corresponding BMP

[2]A programmable logic device.

describes a swing motion[3] followed by a stance motion[4]. In the perspective of behavior based software control the idea of using structures which are in function equal to the command neuron idea, is related to the subsumption architecture and its finite state representations[3].
The idea of combinable BMPs is closer related to the neural assembly theory [12]. This means that dynamically changing groups of cells (more than one) are responsible for the type and the activity of observed behavior. From the behavior based control perspective the analogue to a neuronal ensemble is a behavior ensemble. In the software developers view this can be related to the concepts of the Process Description Language[4] where the overall system behavior emerges from the massive parallism of normally more then one behavior system.
As mentioned above, our approach combines both concepts, the CPGs configured by Basic Motion Patterns and the Reflexes. The CPGs control the leg under *normal circumstances.* By normal we mean, that no exceptions, like an obstacle blocking the path of a leg, during the walking occur. The reflexes are only activated by such exceptions and are used to deal with them, e.g. a reflex, which lifts the leg upward to overcome a detected obstacle.

A. The Idea of Leg Control

The behavioral level has two ways to control the leg (fig. 4). The first one is the posture control, which is mainly used to change the position of the leg while walking, e.g. to stretch/compress the leg in order to walk in a higher/lower position. This is done by taking an additional influence on the nominal joint angle values, which are fed to the motor controllers.
The second part (the CPG) produces the rhythmic motion. A CPG is modeled as a system which consists of a multitude of basic motion patterns. A BMP describes a rhythmic trajectory of the leg in the joint angle space. These BMPs can be simultaneously and differently strong stimulated by the behaviors (e.g. obstacle avoidance) at the behavioral level. This is shown at the top of figure 4.
The CPG produces a "Desired Pattern" by overlaying all stimulated BMPs, e.g. if a pure forward BMP and a pure lateral walking BMP are both evenly strongly stimulated the result is a diagonal walking pattern. By varying the stimulation strength every intermediate state between pure forward walking and pure lateral walking can be achieved. If the higher behavioral level changes the stimulation of the BMPs, consequently a new "Desired Pattern" is produced. This pattern can not be fed directly to the motor controller, but goes through a fading process with the "Previous (desired) Pattern" to result in a smooth pattern transition. The "Previous Pattern" is blended out and the new "Desired Pattern" is faded in. So the "Present Pattern" is for a short time a combination of the "Previous Pattern" and the "Desired Pattern". The current angle values from the "Present Pattern" are then added to the values given by the posture control. The sum is fed to the motor controllers (see bottom of figure 4) .
The motor controllers are based on a motor model and a proportional controller to compute the correct pulse width modulated motor signals. To achieve this the actual measured motor current and voltage are taken into account. Furthermore the error between the angle of the present motion pattern and the angle measured by motor encoders is looped back into the motor controller. On this level of control a set of reflexes is also implemented. The reflexes are meant to deal locally with environmentally induced events, such as an obstacle blocking the path of the leg. They are triggered by the measured joint motor current and the looped back angular displacement error. An example of an reflex is described in section IV.

Crucial for this control is the implementation of the basic motion patterns. In a first approach splined squared sinusiods were used to describe the BMPs. These sinusiods are alterable in the amplitude, the frequency and the phase. The implementation is described in detail in [10].

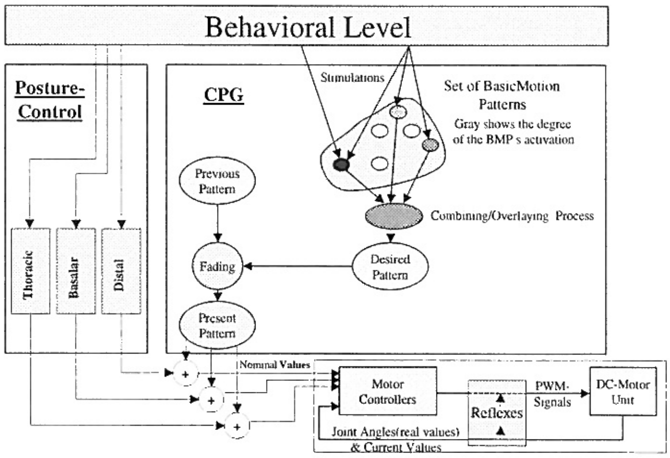


Fig. 4. The Basic Motion Pattern Control Approach

III. An Example of BMP based Motion Production

In the figures 5, 6 and 7 data of the performance of one leg during a run is shown. The solid line is the real angle of the leg, measured with the motor encoders. The angle for the distal and the basal joint increases during elevation. While the angle for the thoracic joint increases during protraction. At $t = 1350$ the leg stands still in a position identical to the leg-positions shown in picture 1. The angle values for this M-shape position are produced by the posture control. So the posture control here adds permanently a value of 37.5^o for the thoracic joint, 122^o for the basal joint and 39^o for the distal joint. First only a Forward Basic Motion Pattern is stimulated. This produces the observable swing and stance motion. Then at $time = 1375$ the lateral walking BMP is additionally stimulated. The combination results in a diagonal walking motion pattern, which can be clearly observed at the thoraric and the distal joint. The amplitude at the thoracic joint is much lower

[3] a swing consist of protraction of the leg while it is first elevated and then depressed
[4] A stance consist of retraction and ongoing low depression

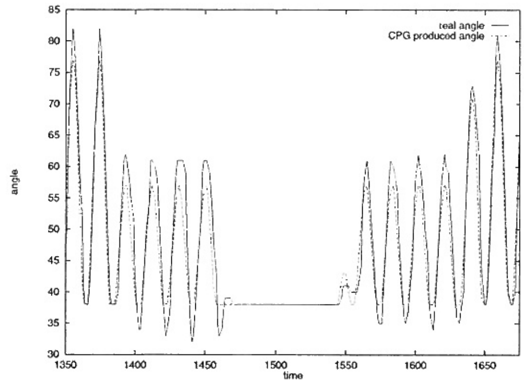


Fig. 5. Thoracic Joint

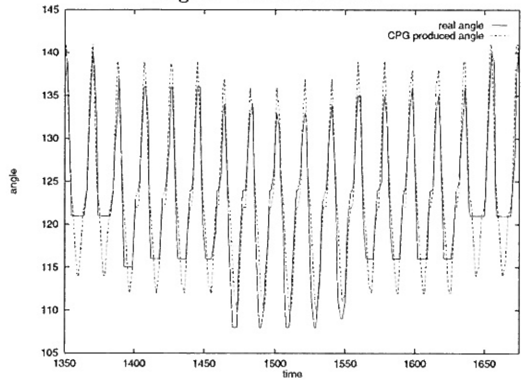


Fig. 6. Basal Joint

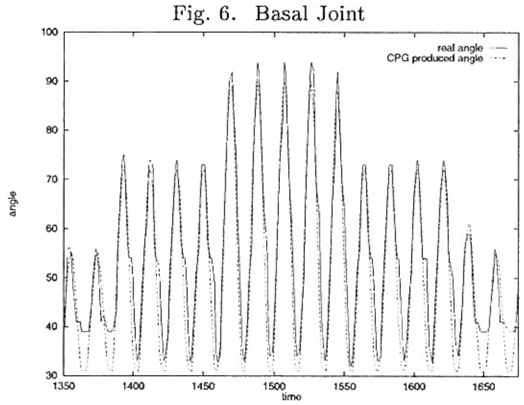
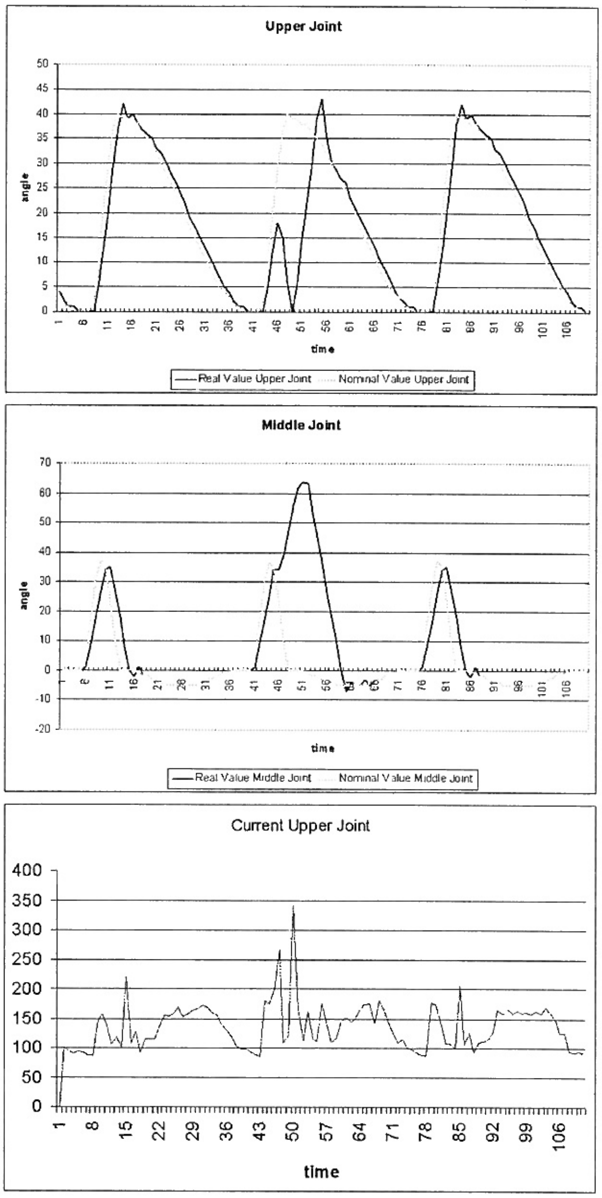


Fig. 7. Distal Joint

Fig. 8. Example of a Obstacle Avoidance Reflex (Upper=Thoracic,Middle=Basal,Lower=Distal Joint)



than in pure forward walking and the amplitude at the distal joint has increased. At *time* = 1460 the forward BMP is not longer stimulated , so only the lateral walking pattern is active. The resulting movement is a pure lateral motion. The distal joint now has reached the maximum amplitude and thoracic joint has an amplitude of zero. Then the same in reverse order happens. Notable is the smooth and fast transition between these different motions. When the activation of the BMPs changes a quick fading process can be observed. The underlying algorithms for the fading and overlaying techniques are described in [10], [11].

IV. An Example for a Local Reflex

The above described motion generation works very well with plain surfaces without obstacles. So the angles generated by the CPG can be seen as a kind of plan for stable walking, if there are no or only little interferences. They are also referred to as the wheeled mode of leg operation[15]. But in rough terrain with obstacles blocking the way of the legs such stereotype motion patterns doesn't work well.

Animals use reflexes to cope with these situations. So transferred to a robot a suitable idea is to integrate a set of reflexes in parallel to the motor controller level, which overwrites for a short and predefined period of time the angle values given by the CPG with its own angle sequence. Here an example for a obstacle triggered reflex is presented. Increasing current values of the thoracic joint [5] and a significant error between the desired angle and the measured angle at the thoracic joint triggers this reflex. Both are strong symptoms for an obstacle blocking the path of the leg.

The reflex works the following way. First the leg retracts

[5]The thoracic joint moves the leg forward and backward.

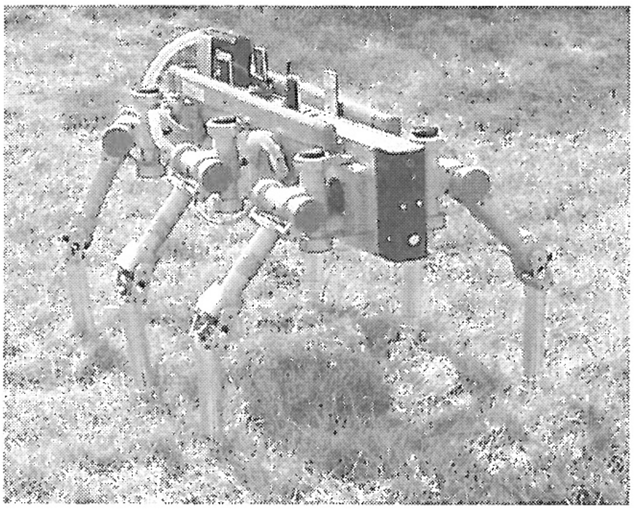


Fig. 9. The 6-legged Robot outdoors in an outstretched position

a bit to get free from the obstacle, then elevates(via the distal and basal joint) and protracts as fast as possible. Thereby the leg will overcome the obstacle, if the obstacle is not higher than the leg can be elevated. Current and joint angle data of this reflex is presented in figure 8. The reflex gets triggered at $t = 46$ and stops at $t = 58$. The reaction time of the reflexes are in a centisecond, because they are integrated into the fast motor controller level.
The three pictures also illustrates how rapid the motor controller returns back to the pattern given by the CPG, after the reflex is no longer active.
It should be noted that this is only one out of a variety of very useful reflexes. We have chosen to describe this "Stumbling Correction Reaction"-Reflex[16] as it is analogous to behavior observable in mostly all walking organisms and also very useful to deal with uneven terrain in our robot.

A. The Posture Control

In order to allow the behavioral level to change the posture of the robot a posture control is active in parallel to the CPG. In contrast to the rhythmic motion pattern produced by the CPG the posture control is not a rhythmic motor control. The posture control enables the higher behavioral level to change the position of each joint of each leg without effecting the angles produced by the CPG. The by the posture control given angles are added to those from the CPG and the sum is fed to the motor controller. Thus it is possible to control the height, the pitch and the roll of the robot during walking.
For example if the robot moves up a slope the pitch control behavior will measure this via the tilt-sensors and lift up the back of the robot by decreasing the posture control angle of the basal and distal joint at the rear legs, which moves the distal and basal limb down. This is done till the pitch level is balanced.

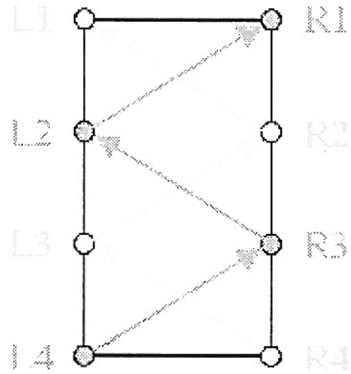


Fig. 10. Walking Gait of Real Scorpions (Bowerman 1971) : The Gait is L4-R3-L2-R1(Group 1) - R4-L3-R2-L1(Group2)

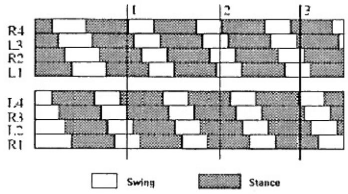


Fig. 11. Phaserelations Between the Legs of a Real Scorpion (Bowerman 1971

B. The Higher Level Control

The higher level of control consist of behaviors to sense the environment, to get commands from an operator and to control the activation of the BMPs, the CPG parameters and the Posture Joint Angles . The higher behavioral level controls the CPGs in the local leg controllers by the following means:

- The phase relation between the local motion patterns, resulting in different synchronization of the motion of the legs. For all experiments the phase relation was fixed based on the results from Bowerman[17](see picture 10). The phase offset between the legs is shown in fig. 11.
- The frequency of the BMPs, resulting in different speeds and in a different number of legs which are concurrently in the swing phase, because of the fixed phase offset between the legs.
- The activation of the different BMPs, resulting in different motions of the leg.

The posture is controlled by the following changeable parameters:

- The height of the robot
- The pitch gradient
- The roll gradient

From these parameters the joint angle values for each joint are computed.
The higher level consists of behaviors like ultrasound based Obstacle Avoidance, compass-based Direction Control, Speed Control, Height Control, tilt-sensor based Pitch and Roll Control.
With the obstacle avoidance behavior the robot is able to detect obstacles with its ultrasound and maneuver around them or walk over the obstacles. It will only walk over ob-

stacles , which are not higher than itself[6].

The Direction Control enables the robot to keep a direction which can be given by an operator or a higher navigation behavior. The Pitch, Roll and Height Controls are used to stabilize the robot while walking. The idea is to equalize the load for the legs. For example if the robot moves up a slope (which can be detected with the tilt-sensors), it will lift up its back in order to keep the center of mass in a favourable position.

The Speed Control is also used to stabilize the robot. In dependency of the quality of the terrain, which can be detected by means of frequency of occurrence of reflex-feedbacks and tilt-sensor measurements, the robot will adjust its speed to stabilize the overall walking behavior. This is especially important for the six-legged robot(see next section).

V. The Outdoor Tests on the SCORPION robots

We tested the systems over different terrain and with different obstacles. We used for both systems the same ambulation control approach. The speed on a plain street is about 12m/min for the 8-legged robot and 16m/min for the 6-legged robot. In even terrain the robots are able to run for an hour with 3.8Ah batteries. In uneven terrain this is drastically reduced to about 25-40 minutes. The 6-legged robot is not as stable while walking as is the 8-legged system. Especially at high speed the reflexes at the foremost legs causes instability. The system tends to tumble forward because of the high forward force momentum. Therefore it was necessary to reduce the speed of the robot, when a reflex gets activated. So the 6-legged robot is faster on plain ground but significantly slower than the 8-legged in rough terrain. With the 8-legged robot we made some more tests with obstacles and in rough terrain. The robot walked over pipes with a diameter of 28cm which is approximately equal to its ground clearance in the highest position of the robot. It walked over different rockbeds consisting of rocks with diameter between 5-45cm. The robot walked in loose sand too. The normal height of the robots while walking is 26 cm. Its maximal height to which they can change while walking is 40cm(ground clearance 28cm).

VI. Outlook

Major enhancement in the performance of the robot will be achieved by integrating additional spring systems in the joints. The springs will work in sequence with the motors to simulate the actuator tension systems in animals. In a first step these motor-tension units will be passive. This means the characteristics of the springs can not be changed during runtime. We will instead determine a suitable spring empirically to serve over a wide spectrum of functionality. In second and third step enhancements we plan, however, to integrate strain gages that measure the strain on the springs and that will allow us to implement full force control algorithms. Also we are surveying different materials that may be used to implement adjustable spring systems, such as certain electro-polymers and springs made from shape memory alloys. Compliance is an effective way to cope with mechanical stress as well as to implement dynamic walking/running gates[13]. The major work over the next year will thus concentrate in the integration of the motor tension units into the existing robot, and of course to implement appropriate algorithms for control to make full advantage of this new feature. In addition the repertoire of the behaviors will be increased to come closer to the goal of an autonomous outdoor walking robot system. We are also working on a model for the CPGs which allows the integration of sensory feedback into the production of the rhythmic motion, which would enhance the walking capabilities of the system.

[6] This can be measured with the ultrasound sensor, when the robot moves to maximum height.

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