

The Bio-Inspired SCORPION Robot: Design, Control & Lessons Learned

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1. Introduction

This chapter will review the SCORPION robot project (Kirchner et al., 2002). The goal of the SCORPION robot project was the development of a very robust eight-legged robot, which is capable to traverse very steep and unstructured terrain without high-level planning or using complex exteroceptive sensors, e.g., a laserscanner.

The SCORPION robot is now a field-tested system which was successfully deployed in various kinds of outdoor terrain (e.g. rocky, sandy).

Currently, the SCORPION robot design is in discussion to be used in future extraterrestrial exploration missions into steep craters on the Moon or Mars (Spenneberg et al., 2004).

In the following sections we will describe the steps we undertook to achieve this goal.

In Section 2, we will describe the different mechatronical design steps and discuss briefly the problems faced and the solutions developed.

Then we will discuss in section 3 the different possibilities for a control approach of a legged outdoor robot and describe the developed hybrid bio-inspired approach (Spenneberg, 2005a), which combines posture control with CPG (Central Pattern Generator)-based control and reflex control.

Subsequently, we will discuss the achieved performance. Concluding, we will discuss the lessons learned and future steps to utilize the full potential of walking and climbing robots (section 4).

2. Mechatronical Development

For the development of the SCORPION robots, real scorpions have been used as an archetype. Scorpions belong to the class of spiders and have eight legs.

The SCORPION project started in 1999.

Since then, one integration study and four systems have been built in an iterative design approach to achieve the final robustness of SCORPION IV.

Integration Study (1999)

Source: Climbing & Walking Robots, Towards New Applications, Book edited by Houxiang Zhang, ISBN 978-3-902613-16-5, pp.546, October 2007, Itech Education and Publishing, Vienna, Austria

The first full system which was built was the integration study in autumn of 1999 (see Fig. 3). This system was used to test the interaction between electronics and the first software concepts together with a first version of 3DOF (degrees of freedom)-legs. The legs consisted of a thoracic joint for pro- and retraction, a basalar joint for elevation/depression of the leg, and the distal joint integrated into the basalar segment driving the distal segment via a bevel gear (see Fig. 1).

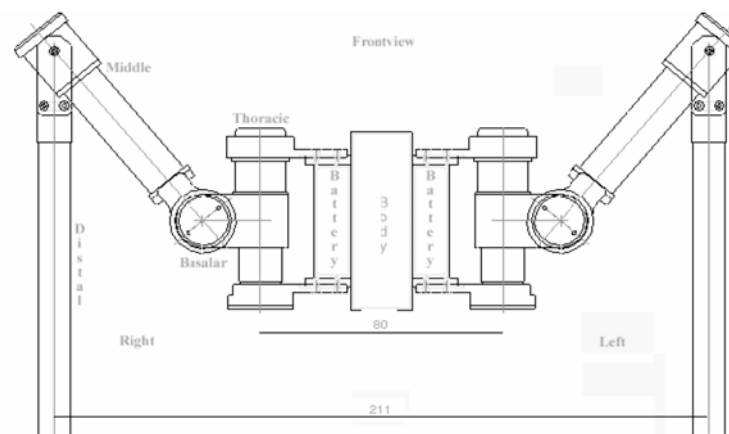


Fig. 1. The mechanical design of the SCORPION legs. This front view of the robot shows left and right side legs with the body (SCORPION II) in the center. Each leg consists of 5 parts: 1) thoracic joint, 2) basalar joint, 3) distal joint, which is integrated into the middle segment driving the distal segment via a bevel gear.

This reduction of down to three DOFs is supported by studies on real scorpions (Bowerman, 1975), which describe that mainly only three joints are used for ground locomotion. (Ayers, 2002) and (Cruse et al., 1999) are supporting the idea that for an adequate model of invertebrate walking three joints per leg are sufficient. The existing additional joints are mainly used by the animals for other functions, e.g., ingestion or prey hunting. The legs of the integration study have been developed using mainly light composite materials, e.g., POM and small 10mm motors with plastic gears. The developed control hardware consisted of custom-made microcontroller boards featuring C164 and C167 boards.

The integration study has been used for aerial walking tests on a supporting stand.

It has been extremely useful to test the low-level software drivers and first locomotion control concepts very early in the project. Furthermore, it allowed testing the concepts of using nine microcontrollers in a network. Eight C164, one controlling one leg, were used and one C167 for the central control and to interface the robot to an external operator. These microcontrollers were connected via a CAN-Bus.

Figure 2. depicts this hardware architecture which was used till SCORPION III.

This configuration allowed high flexibility for simple testing of different concepts thus ensuring fast software development.

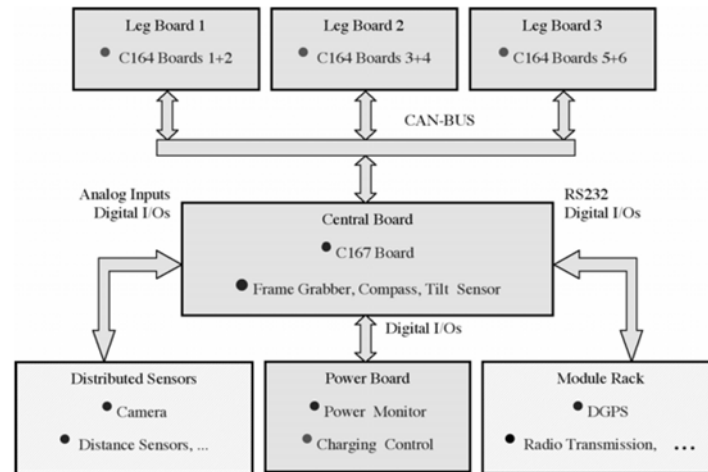


Fig. 2. Hardware architecture of the Integration Study and SCORPION I-III

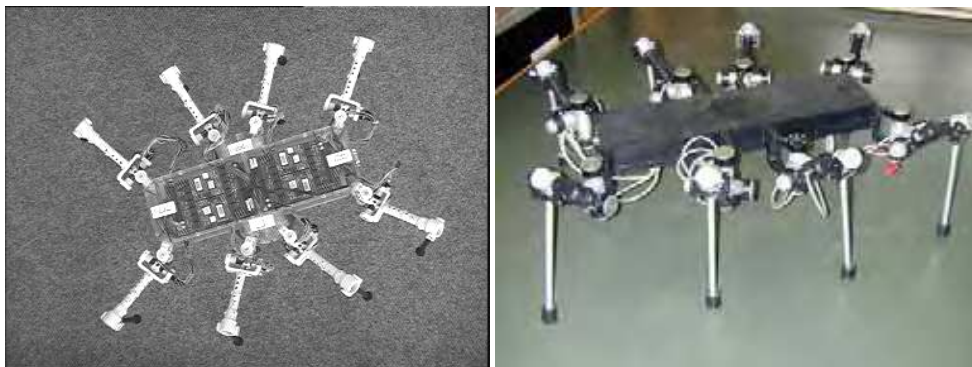


Fig. 3. (a) SCORPION Integration Study

(b) SCORPION I

SCORPION I (2000)

In the meantime, a new leg and corpus design was developed which resulted in the first robot prototype "SCORPION I", weighting 9.5 kg. It used 18mm motors of the company Faulhaber with approx. max. 2Nm torque each.

The design of the legs was fully shielded with special gaskets to allow outdoor deployments.

For the mantle material of the legs aluminium was introduced. Because of the shielded design the system was able to work underwater, too. Fig. 3. (b) shows the robot.

The new motor-gear combinations produced enough force to carry the body, but the bevel gear in the distal segment were worn out after a dozen operation hours, because the production accuracy of the bevel gear modules had been too low (this was addressed in SCORPION II).

Thus, as a simple solution, we fixed the distal joint in a position where it was perpendicular to the ground in an M-shape position (like in Fig. 1) and used only the upper two joints for

further experiments. In this configuration, with using only two motors per leg, the robot was able to walk up to 10cm/s and inclination up to 10°. It was furthermore able to overcome obstacles up to 5cm.

The sealing of the system worked very well, but if you are in the early development of a robot, we recommend not sealing a system, because of the disadvantages regarding maintenance time.

A further result of the experiments was that the basalar joints were working in most experiments at their limits. Due to the body, the contact points of the contra-lateral legs were too far away from each other. This resulted in a lever applying high forces to the basalar joint for just keeping the body above the ground. To reduce this, the next system needed to be more slender.

SCORPION II (2000)

In the winter of 2000 SCORPION II (see Fig. 4) addressing the above described problems was completed.

A mayor challenge in the design of the leg modules was the constraint to build an outdoor-capable walking machine with shielded actuators while at the same time achieving a good ratio between the leg weight and its lift capacity. In the design of SCORPION II we have achieved a ratio of 1:8 incorporating shielding from the environment. This was possible by using high ratio planetary gears in combination with a new powerful DC-motor resulting in 3.5 Nm max torque. The increased ratio was necessary as we intended to be able to climb obstacles, which would exceed the robot's own height. Thus, in certain situations single legs would have to be able to pull/push at least 3/4 of the robot's weight.

Another aspect in leg design is the speed of the leg to react fast enough to disturbances from the environment. So simply increasing the gear ratio does help to gain the torques desired but it also decreases the reactive speed of the module.

To fulfill all of these goals, we increased the produced torque and speed of the actuators by using the new 22mm motors from Maxon Motors and kept the gear ratio we used in SCORPION I.

Another optimization, which was conducted to increase the outdoor robustness, was to pass the cable harness mainly through the inner leg (via new inner cable ducts) instead of keeping it outside of the leg. This significantly reduced the risk of getting entangled with the leg.

In addition, we developed a slender aluminium-body aimed at maximum stability and easy maintenance.

In its side-pockets, this system contained NiCD-batteries with 28.8 V and 1.8Ah enabling an operation of 30 minutes with full speed of 20cm/s. It was able to climb up inclinations of 15° and to overcome obstacles up to 20cm.

The system was equipped with an ultrasound-sensor in the front and a camera-system as well at the front as on an optional sting which was connected to the back of the robot. To control the robot it was equipped with a bidirectional DECT-radio-link. In addition to the basic motion control featuring CPG, posture, and reflex control (see section 3), the software of this system included first higher level behaviours, e.g. autonomous obstacle avoidance and a balancing behaviour based on integrated inclinometers.



Fig. 4. SCORPION II in the SWRI rockchannel



Fig. 5. SCORPION II as a six-legged system

This system was matured to a degree that realistic outdoor tests were conducted, e.g. on the Small Robotic Vehicle Test Bed of the Southwest Research Institutes (SWRI) in San Antonio (TX, USA). These tests gave valuable input for the next design steps. In principle, such outdoor tests carried out together with impartial observers and on an unknown test site are extremely helpful during such projects. They help to identify very quickly the real performance of systems which normally are tested only under lab conditions.

On the basis of the eight-legged design, for comparison tests a shorter six-legged version was built. In Fig. 5. this version with an additional pack of batteries is shown. The major result of this comparison is that due to the reduced weight the six-legged version is faster on flat terrain, but because of the loss of static stability in comparison to the eight-legged robot, the six-legged one is slower in steep terrain. There, its walking patterns have to be reduced to low-frequency patterns, where at any point of time only one leg is in the air in order to keep the necessary stability.

SCORPION II was already a robust system, but some of the outdoor tests showed that the rigid body was a source of problems, e.g. for steep stair-climbing. Furthermore, the system lacked a good sensor for ground contact detection, which led to a suboptimal stance motion in uneven terrain. At that moment it was only possible to monitor the temporal behavior of the current of the basalar joint to estimate whether the ground was hit, which is very unreliable without a model of the robot in its environment.

In addition to this, the system had no compliance yet, which resulted in undamped external forces which were sometimes higher than the specified maximum forces for the gears, thus reducing the lifetime of the legs.

SCORPION III (2001)

Therefore a different design was developed to address these issues, which resulted in SCORPION III finished in autumn 2001.

As opposed to the other SCORPION robots, this system did not have one single rigid body but consisted of three body segments linked by rubber buffers. This design enabled the system to adapt automatically to its environment, which on the one hand is an advantage regarding shock reduction and ground adaptivity, but on the other hand a problem for the control, since the body deformation has to be taken into account.



Fig. 6. The flexible SCORPION III



Fig. 7. SCORPION IV

Therefore, for such a construction we advise to implement sensors to measure the deformation.

Another change was to remove the bevel gear design to actuate the distal segment. SCORPION III used three identical motor tubes for each joint (see Fig. 6.) which reduced production- and maintenance-costs.

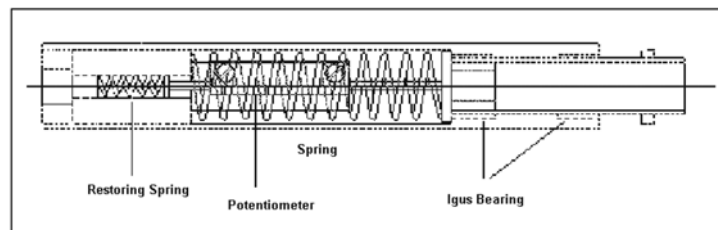


Fig. 8. New compliant distal segment

In addition, compliance was integrated into the distal segment of a leg (see Fig.). The distal segment was manufactured as spring damped chamber with a built-in potentiometer. This approach enabled us to measure, contact, and load on individual legs, while the spring mechanisms acted as a damping component to reduce in combination with the flexible body the impact of high forces on the leg.

During the SCORPION project we were not able to thoroughly enhance and test this design, because the new, longer planned, and light-weight MPC555+FPGA controller board, which was optimized for our computational needs and replaced the network of five boards with nine microcontrollers (see Figure 2.) became available by spring of 2002.

Due to its length of approx. 40cm, it did not fit the design of the SCORPION III.

Therefore, we stopped working on SCORPION III, which is a very interesting system and if it would be equipped with sensors to measure the deformation and appropriate models for feeding this information into the control loop, it would be a very robust and adaptive system.

SCORPION IV (2002)

Most of the enhancements from SCORPION III entered the design of SCORPION IV. For SCORPION IV (see Fig. 7.), the body concept of SCORPION II was slightly modified to be equipped with 3.0Ah, 28.8V NiMh batteries in the side pockets and with the new hardware board (see Fig. 9.) which was introduced in spring of 2002.



Fig. 9. SCORPION control board featuring an MPC555 and a Xilinx Virtex E FPGA

This six-layered board combines all features of the former control boards and provides additional options. In comparison to the former control network, it saves 1.5kg and 60% of the volume. Its speciality is the usage of a reprogrammable FPGA to read in all signals from up to 32 joints: motor current, position, as well as the values from the pressure sensors. These values are used in a PID-controller (control frequency of 2 KHz) programmed into the FPGA to produce PWM-signals for the control of up to 32 motors.

The main features are:

- 40Mhz 32Bit MPC555 Power PC Microcontroller with MIOS & CapCom-Units,
- 64 TPU-Channels, 2 CAN-Interfaces, 3 serial ports
- Up to 81 A/D-channels
- Virtex E XCV400E (432 Pins) FPGA with approx. 570.000 gates connected directly to the memory bus of the MPC555 – data exchange via an Dual-Port RAM which is programmed into the FPGA
- 8 MB Flash EEPROM, 4 MB SRAM memory on-board
- 32 DC-motordrivers (right side of the picture) with up to 5A max.
- 32 on-board current sensors
- 1.8V, 3.3V, 5V und 15V power supply
- 12-36V operating voltage, power consumption <6W
- Direct programming of the FPGA form the MPC555 via SelectMAP Mode (time < 1s)

This board allowed reducing the width and length of the SCORPION II design.

To increase the stability of the system and to reduce weight, the body of SCORPION IV got a rib-design. This also increased the ability to dissipate heat.

In principle, the design shown in Fig. 7. is the design of the SCORPION robot till today.

In the following years, minor modifications to improve the performance were carried out.

We integrated a two-spring-system into the legs for increased sensor response of the ground sensor and better shock-reduction. Furthermore, in all systems we used motor encoders for the joint position measurement, which meant that calibration was needed. In 2003 we exchanged these with high-precision potentiometers, which are working very reliable.

Summing up we can say, that the iterative development approach was a full success. The SCORPION IV system is still in use and part of research projects, where we are using this robot for crater exploration experiments in the context of space applications. A copy of this system is also installed at the NASA Ames research centre.

The performance results gained with this system are described in section 4, following our discussion of the control approach.

3. Development of the Control Approach

There are already a lot of different approaches for controlling locomotion in multipods.

These approaches can be divided into three different groups.

The first group contains all those approaches which are using as accurately as possible physical models for the exact control of kinematical chains like the model-based approaches for industrial manipulators (model-based approach).

The second group comprises all approaches which are using in their core bio-inspired control mechanisms (bio-inspired approach).

The third group enfolds adaptive approaches which are using learning algorithms to develop locomotion control mechanisms (adaptive approach).

Examples for the adaptive approach are

- (Kirchner 1998) using a hierarchical Q-learning for evolving a goal-directed walking behaviour on the six-legged robot "Sir Arthur".
- (Maes 1990) describing an early locomotion learning experiment on the walking robot "Genghis" based on positive and negative feedback and elementary locomotion building blocks.
- (Ispeert 2005) describing the use of evolutionary algorithms to develop locomotion mechanisms for a salamander robot on the basis of oscillator models.

The work on adaptive approaches is interesting, but, in principle, here the walking robots are only used as a case study for more general learning algorithms. The work on using learning algorithms for walking robots does not provide us with a general architecture for programming walking robots. Thus, in the following, we will focus deeper on the bio-inspired and model-based approaches and compare them.

Examples for the model-based approach are

- (Loeffler 2003) describing a control approach with three different layers. On the highest layer, the trajectories for the limbs of the two-legged robot Johnnie are computed. This is based on three basic walking patterns: standing, walking, jogging. These patterns are divided into their different phases (e.g. swing-, stance-phase). For all of the walking patterns, optimized trajectories are computed offline and can be accessed from an online-table. Because of deviations, an additional reduced dynamic-model was implemented (second level) on an external Pentium III (800 Mhz) which is fed with the data from the orientation sensor and used to

compute adaptations of the joint trajectories. On the lowest level, a PID-controller is implemented which controls the joint.

- (Go 2005) is a recent example of using a kinematical model for the control of a six-legged robot. Because of the needed constraints to find a closed solution for the inverse kinematical problem, this algorithm cannot be used in uneven terrain. It assumes for example that the body coordinate system is kept parallel to the ground all the time, which is impossible on uneven terrain. In addition, slippage at the foot tips is not foreseen in the model.

What is described in (Go 2005) is a general problem of the model-based methods. They normally lack the information required from the environment in order to model exactly the behaviour of the system in its corresponding surroundings and, furthermore, they are computationally expensive. Without well-defined constraints like used in (Go 2005), a closed solution cannot be found, resulting in applying very time-consuming iterative methods which are unusable for real-time control.

If we look at systems like the SCORPION robot, the use of a model-based approach seems also extremely prudent because these multipods are statically stable in almost every situation. This means that at every time step the system can be frozen in its motion while at the same time keeping its current position and orientation. Taking a two-legged or four-legged system this is more often than not the case, so that one has to take the dynamics into account.

But for a six- or eight-legged system more elegant and simpler solutions can be found which lead us into the field of bio-inspired concepts.

Even the most primitive biological systems solve problems that reach far beyond the capabilities of today's technical systems (Kirchner, 2002). The biomimetic approach to robotics is the attempt to apply solutions created by evolution to technical systems. This approach is not restricted to mechanical engineering but includes and puts emphasis on the behaviour of autonomous systems, i.e., the algorithms that map from sensory stimuli to motor acts. Well-known approaches can be found in (Cruse et al., 1999, Beer et al., 1997, Spenneberg, 2005a, Gassmann et al., 2001).

These approaches are using aspects of decentralized control and neglect the need of complex internal models; instead they are primarily reactive approaches.

In the following, the development of our bio-inspired PCR-approach for the SCORPION robots is described.

It is based on major identified low-level locomotion concepts found in biological systems which are Central Pattern Generators and reflexes and posture primitives.

CPG-Control

A Central Pattern Generator (CPG) is the major biological motoric mechanism to control and to produce rhythmic motion. They are characterized by the ability to produce rhythmic motion patterns via oscillation of neuronal activity without the need of sensory feedback (Wilson, 1961).

However, many CPGs get sensory feedback, e.g., about the load and the position on the corresponding driven joint.

Thus CPGs are mostly used for closed loop control of the rhythmic motion of actuators.

To modulate the behaviour of the motion, their rhythmic patterns can be changed in frequency, phase, and amplitude.

This functionality based on biological neurons and executing muscles cannot be transferred directly on a walking robot because it possesses motor-driven joints instead of muscles.

From the robotics point of view it is reasonable to develop a more abstract CPG model which captures only the basic principles of the functionality of CPG motor control.

The CCCPG-approach (Ayers 2002) is a possible step in that direction, but its mechanisms are tightly connected to the research on the organisation of the neuronal circuits of lobsters and the Nitinol-actuators used in the underwater lobster robot for which the CCCPG-approach was developed.

Instead, we pursued the goal to formulate a more general CPG-model which has no direct biological archetype.

Important features of CPG control is the ability to describe and hence produce motion with rhythmic signals, which can be modulated in their phase, frequency, and amplitude, to change the resulting motion in its timing of execution, its duration, and its strength/speed.

In our model, the closed loop control (via sensory load and position feedback) can be implemented by a PID-controller.

If we use a modifiable rhythmic trajectory to provide set values for a standard PID-controller, which receives the position signal from the corresponding joint, we have a closed loop control of the rhythmic motion in different load states comparable to the behaviour of a real CPG.

Recapitulating, this means that our abstract CPG-model consists of a controller-module and a unit to produce rhythmic trajectories in the joint angle space.

In a first attempt to describe the rhythmic trajectories we used splined sinusoids (Spenneberg & Kirchner 2001, Spenneberg & Kirchner 2000).

This worked very well for first walking experiments, but if more complex pattern, consisting of a multitude of splined sinusoids a more general and flexible method to produce a rhythmic function is preferable.

Therefore we chose to describe a CPG-Pattern \mathbf{P} as a function of part-wise fitted together third-order polynoms of the form:

$$y(t) = \sum_{a=0}^n k_a \cdot t^a \quad (1)$$

A part X is described by the coefficients of the polynom $k_a(X)$, its length $l(X) \in \mathbb{N}_0$ on the x-axis, the phase offset $\Theta(X) \in [0,1]$, its scalability $S(X) \in [0,1]$, and an optional subpart-list, if the part is constructed by subparts.

A complete rhythmic pattern is then described by a list of parts with the end of the list pointing to the start of the list.

To describe a part, Bezier-polynoms are used which are described by the following equation:

$$P_0 \cdot t^3 + P_1 \cdot 3 \cdot t^2 \cdot (1-t) + P_2 \cdot 3 \cdot t \cdot (1-t)^2 + P_3 \cdot (1-t)^3 = P \quad (2)$$

P_0 and P_3 are supporting points and P_1 and P_2 are control points of the curve.

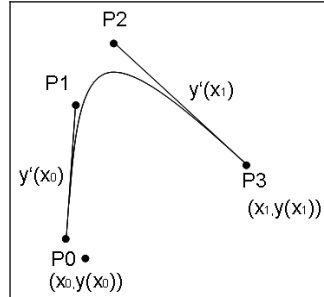


Fig. 10. A Bezier Curve

This coherence is illustrated in Fig. .

Bezier curves are smooth (optimal for DC-motor-control) and the controllable gradients at their end-points allowing a smooth transition from one part to the next which make them favourable for motor control.

If, like here, the Bezier curves are used only to describe a trajectory in the 2-dimensional joint angle space in dependence of the time t , these curves are functions which reduce the computation of the polynomial coefficients:

$$\begin{aligned}
 k_0 &= y_0 & (3) \\
 k_1 &= y'(x_0) \\
 k_2 &= \frac{(2y'(x_0) + y'(x_1)) \cdot x_1^2 + 3(y_0 - y_1) \cdot x_1}{-x_1^3} \\
 k_3 &= \frac{2y_1 - (y'(x_0) \cdot x_1 + y'(x_1) \cdot x_1) - 2y_0}{-x_1^3}
 \end{aligned}$$

In this solution, P1 and P2 are only used to compute the gradients $y'(x_0)$ and $y'(x_1)$.

A position-algorithm computes in every time-step t for the current Part X_a of the whole pattern P (consisting of n parts and with a offset Θ) a simple equation (see Spenneberg, 2005a for details) to get the actual position (joint angle) in the rhythmic trajectory.

For a smooth transition between parts, we defined typical constraints namely that the connection points between the parts have the same value and that the first derivative of them is identical.

To get an even more compact way of describing trajectories, we distinguish only two types of supporting points, (Type 0)-points where $y'(x)=0$ (extreme points) and all other points (Type 1).

The gradient of the Type 1 points is given by the gradient of the line through its direct neighbour points.

The length $l(X_a)$ of a part X_a is equivalent to the difference $x_1(a) - x_0(a)$.

An example of a resulting pattern is shown in Fig. . The following parameters have been used (x, y, type): $\Theta = 0$; $X_0 = (0, 0, 1)$; $X_1 = (5, 40, 0)$; $X_2 = (10, 0, 1)$; $X_3 = (30, -20, 0)$; $X_4 = (50, 0, 1)$.

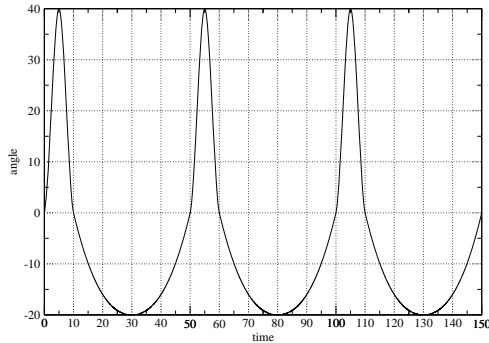


Fig. 11. Example Lateral Leading Pattern (Basalar Joint) using the Bezier Spline approach

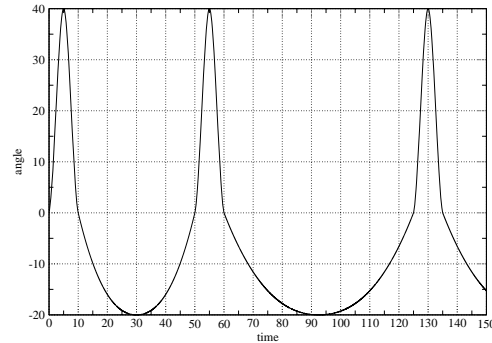


Fig. 12. Example of Period scaling

To modulate such a pattern in their phase, their frequency, and their amplitude, functions can be found easily. In principle, this is done by scaling the coefficients of the polynomial or by applying an offset to the polynomial. More details can be found in (Spenneberg, 2005a).

As we have seen from examples in biology (Bowerman, 1975), in some cases not the whole pattern has to be scaled, e.g., observations on invertebrates have shown that they change their swing-period only slightly when the step-period is prolonged.

To map this property, we introduced the scalability $S \in [0,1]$ for each part, which indicates if this part X is scaled, when the whole Pattern P is scaled.

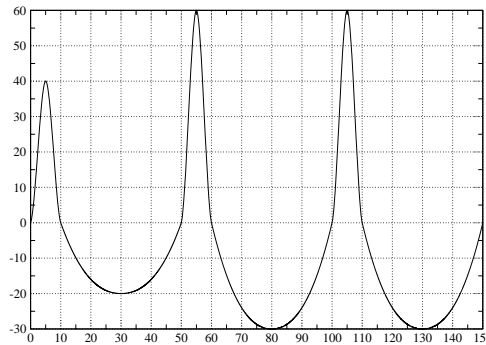


Fig. 13. Example of amplitude scaling

Figure 12 shows an example where the period of the whole pattern was newly scaled at $t = 50t$, but the first parts were configured as non-scalable $S(X_0) = S(X_1) = 0$ Figure 13 shows an example where the amplitude of the pattern is scaled. An example for defining patterns with offsets to let the robot walk forward is presented in Figure 14.

Recapitulating this CPG-model allows the production of rhythmic and smooth motion patterns on the basis of Bezier-splines, which can be described very compactly by their

supporting points and their types. These patterns can be modulated easily in their phase, amplitude, and frequency. In addition, parts which have not to scale can be selected.

In addition, this approach allows also the combination of CPG-patterns or a smooth fading between different simultaneously active patterns. Therefore, patterns have an activation and the activation of the hitherto pattern is decreasing over a certain period and the activity of the new pattern is increasing (Spenneberg & Kirchner, 2001).

As long as more than one pattern is active in parallel, the current position is computed as an average of the current position in both patterns weighted with their activity. The same idea can be used when more than one pattern is active. This allows, for example, transition between lateral walking and forward walking as well as the overlay of a lateral walking pattern with a forward walking pattern, which results in a diagonal walking pattern (see also the combination of patterns in Fig.).

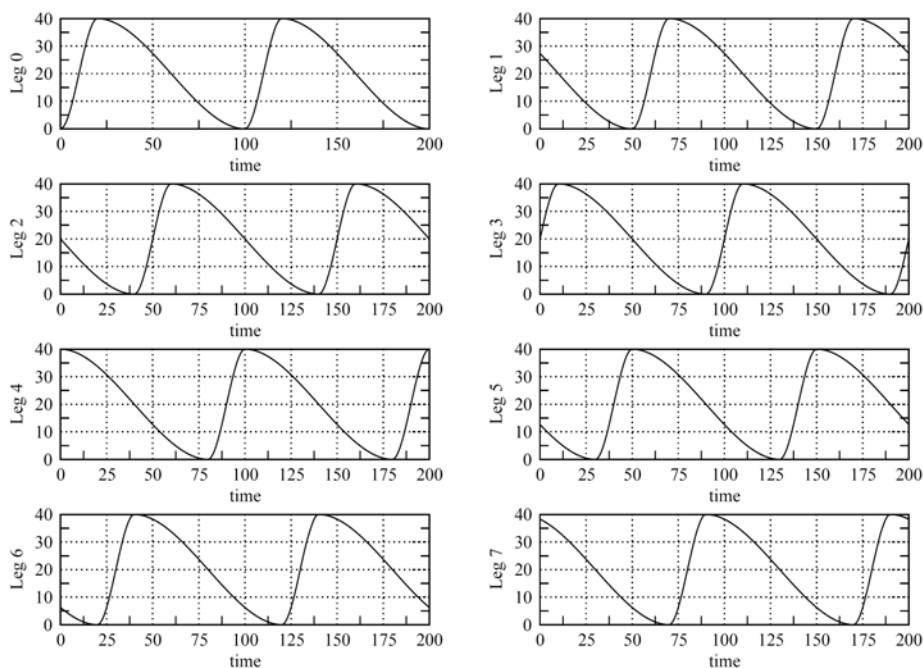


Fig. 14. SCORPION forward/backward walking pattern (Left: Thoracic joint; Right: Basalar joint) using the Offset from (Bowerman, 1975) using the CPG-model

More examples for using this CPG-model can be found in (Spenneberg et al., 2004 and Spenneberg et al., 2005a).

The Posture and the Reflex Model:

To control the posture of a joint, we integrated the ability to apply an offset to the y-Axis (joint angle) of the rhythmic patterns (see Fig.). If there is no rhythmic activity, we can also use the posture control for direct control of each joint, e.g., for manipulating objects.

Biological Reflexes are neuronal mechanisms which transform sensory input into motoric action - often with using one or more interneurons. The motoric action depends mostly on the strength of the stimulus and the interneuron circuit.

In contrast to the common assumption that reflexes are fixed reactions, it is possible that interneurons can be reprogrammed and thus change the motoric action (Reichert 1993).

In addition, the occurrence of reflexes is often sent to higher neuronal centres.

Therefore, a simple reflex model has an input-, activation-, and a response-function (see Fig.).

Furthermore, the reflex can be controlled via control signals from higher levels, e.g. the threshold can be changed to weaken the reactivity of the reflex in certain states. In the lateral walking, for example, a stumbling correction reflex (Forssberg, 1979) which is reasonable and found in forward walking would not work appropriately or produce an adverse behaviour. Therefore this reflex should be inhibited during lateral walking by applying proper control signals.

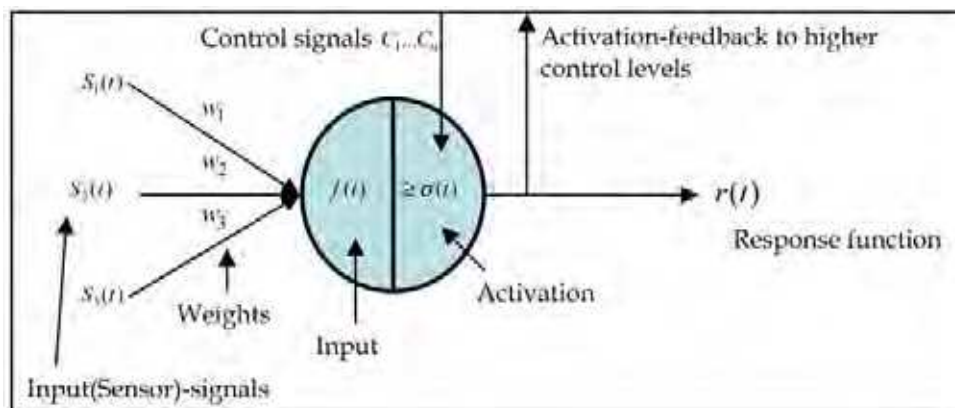


Fig. 15. Reflex model

The control signals C_i are given from the outside (see Fig.).

The response function $r(t)$ is activated when $a(f(t))$ is positive, and is responsible for the reaction of the controlled motor-joint(s).

An example of the reflex is the well-known tumbling correction reflex implemented in the SCORPION and ARAMIES (Spenneberg, 2006) robot. This reflex and corresponding data can be found in (Spenneberg & Kirchner, 2001).

It is only active in the first two thirds of the swing phase of a leg. If the leg hits an obstacle, a response is triggered which lifts the legs higher up to overcome the disturbance.

In the stance phase this response is not triggered when the leg is disturbed. The input for the input function is the current drawn by the shoulder motor which drives the leg forward (thoracic joint of the SCORPION). Because of the low load on the leg in the swing phase, the threshold is chosen low (via the control signals), thus disturbances (blocking the motor) will activate the reflex. In the stance phase the threshold is set high, thus resulting in no activation of the reflex. The response function, the real joint angle, and current data during a reflex activation in forward walking are shown in Fig..

Integration of the Models into a General Framework

All components, rhythmic motion control (using the CPG-model), posture control, and reflex control are integrated into the motoric level of a joint as depicted in Fig..

In the PCR (Posture-CPG-Reflex) approach, each joint has its own motoric level which is modulated and coordinated by the behavioural level (see Fig.).

The input values for the motoric layer are:

1. the activations for each CPG-pattern ACT_i and the corresponding amplitudes A_i (of pattern i), the execution period P_{Leg} (identical for the whole leg), and the phase Ph_{leg} (identical for the whole leg) for the rhythmic production part
2. the offsets O_j and its corresponding weights W_j for the posture control part
3. the control-signals C_r for the reflex part.

Reflex Behavior

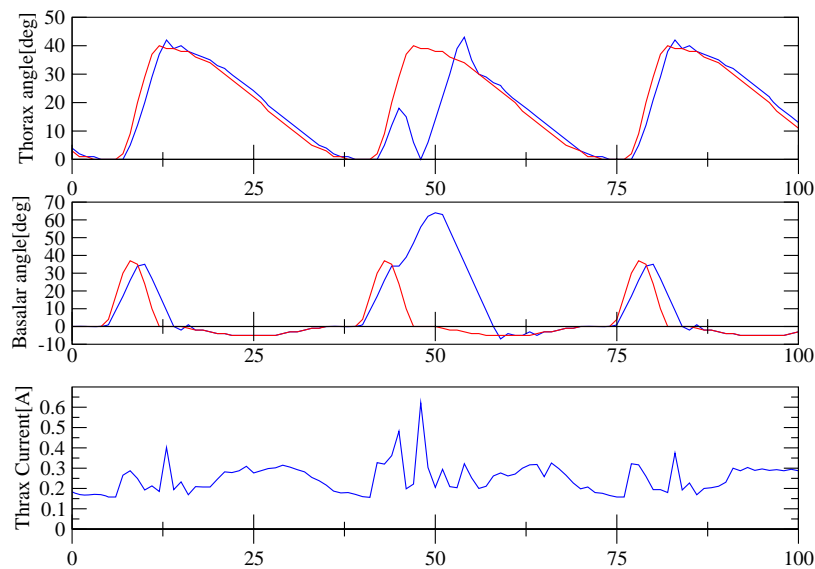


Fig. 16. Data of the stumbling correction reflex (red: set values from the CPG, blue: real values): As soon as the current of the thoracic joint exceeds the threshold of 0.45A the reflex gets triggered and overwrites the signals from the CPG. The reflex function moves the leg back and up and then as fast as possible forward. After 12 time-steps the activity of the reflex declines and the CPG takes over control.

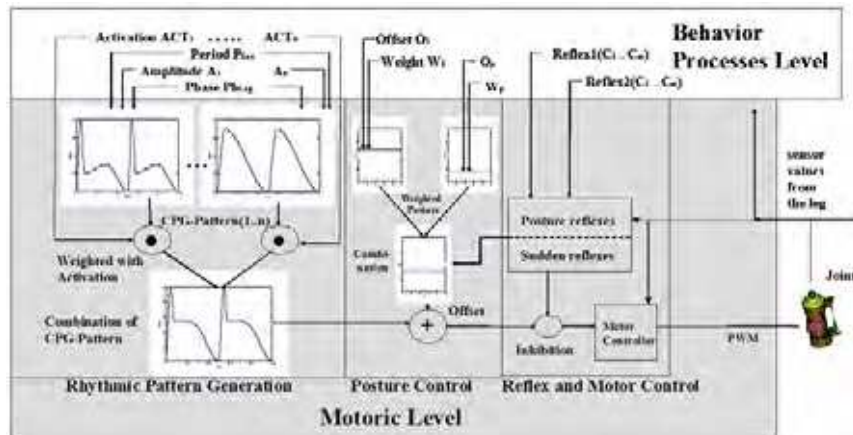


Fig. 17. Motoric layer controlling one joint

On these input values, several behaviour processes can take influence at the same time.

The result is computed by a merge-process which uses a weighted sum principle (for further details see (Spenneberg, 2005b)).

In the rhythmic pattern generation part, all active CPG-patterns are weighted with their activation resulting in one final pattern which is the weighted sum of all active patterns, e.g. if a forward walking pattern and a diagonal walking pattern is active simultaneously and with the same strength the result will be a diagonal walking pattern.

This final pattern can then be offset regarding the angle by the Posture Control.

Again, in the Posture Control we can have simultaneous and weighted influences which form one final offset for each joint. After the offset is applied, this pattern is fed to the motor controller which moves the joint according to the given trajectory, if no inhibitions from reflexes take place.

Therefore, the motor controller gets the current and position values from the joint.

The reflexes also get these values. We implemented two types of reflexes. Type-1: Reflexes which control the posture and are almost all the time active (low threshold). They take influence on the offset via their response function to control, for example, pitch and roll of the system or to keep the distal joint perpendicular to the ground when the SCORPION robot walks forward. Type-2: Reflexes, like the above described "Stumbling Correction Reflex", which inhibits the values from the rhythmic and posture control and writes its own values to the motor controller.

To coordinate the joints via their motoric layer, the behavioural layer is responsible (see Figure 19).

For the rhythmic locomotion coordination motor programmes are introduced.

An example of a motor programme, Forward Walking, is presented in Fig..

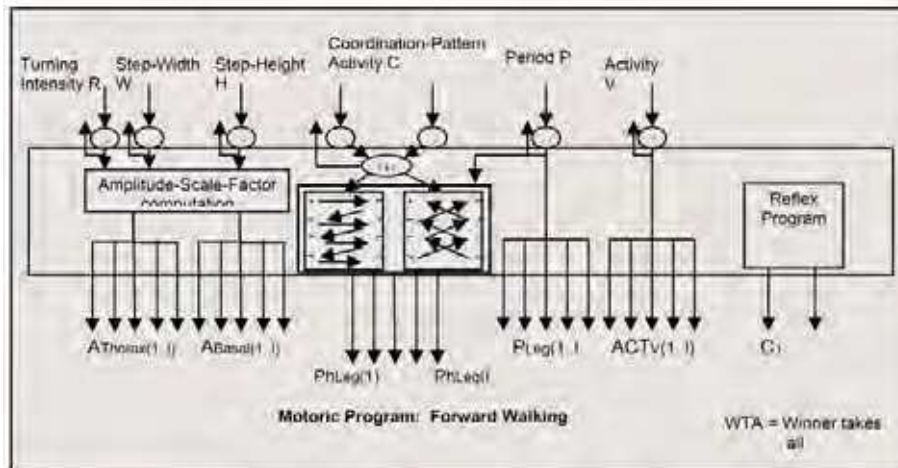


Fig. 18. Example of a motoric programme

A motor programme serves as an interface between the motoric layer of each joint and the higher levels of control and is responsible for the control of a complex movement.

For example, the interface of the forward walking motor programme provides the higher level with an abstraction which makes the control of forward motion of a legged system almost as simple as the control of a wheeled system. The controllable input parameters are: The turning-intensity R (which corresponds to a turning radius clock-/ or counter-clockwise, the step-width, the step height, the Activity C_i for the different coordination patterns (e.g. wave pattern, tetrapod-pattern, Bowerman-coordination pattern (see Bowerman, 1975)), the execution period P (determining the step frequency), and the activity of the motor programme. To control the turning radius as well as step width and step height, new amplitudes for the CPGs are calculated and sent to the corresponding patterns at the motoric level, the coordination pattern is realized by sending the corresponding fixed phase offsets to the CPGs of the different legs. The activities as well as the period are passed without further processing to the corresponding CPGs on the motoric layer.

The motor programmes are modulated by behaviour systems (BS) (again more than one BS can take influence on the input values of a motor programme) implementing more complex functions, e.g., an obstacle avoidance, which is based on a distance sensor.

For the posture control we have a comparable interface, the posture programmes. They are sensory motor loops modulating the posture control of each joint, e.g. to control a certain height of the overall robot (Body Height Control) or a certain tilt (Tilt Control).

An overview of this architecture is presented in Figure 19.

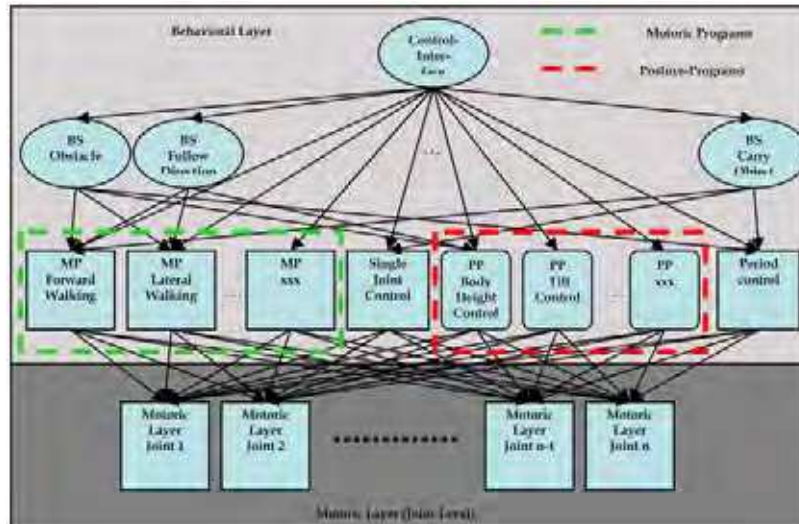


Fig. 19. Overview of the software hierarchy (Black arrows are showing simultaneous influences taken onto the input values), on the top layer a external control interface is shown, instead of this interface a planer can be used in the future.

One advantage of this modular approach is that via the abstraction of the motoric layer and the motor and posture programmes a legged robot can be controlled as easily as a wheeled or tracked system and thus a lot of the methods already developed on wheeled platforms can be reused.

In addition, the approach provides very flexible and potent interfaces on each level. For the implementation of this control approach on our hardware platform (featuring the MPC555) we developed a special microkernel which supports this kind of behaviour-based architecture. Here, the communication between the processes by using the merging based on a weighted sum principle is among other merging functions already supported on the microkernel level. For further details see (Speneberg 2005b).

Results

During the last years we did several tests with the SCORPION robot. In addition we successfully tested the approach on four-legged systems, i.e. the robots AIMEE (Albrecht et al., 2004) and ARAMIES (Speneberg et al., 2006).

The SCORPION IV can now move with up to 30cm/s which is half a body-length per second. This speed-enhancement is partly based on the integration of compliance into the distal joints, which allowed together with optimized CPG-patterns running at 1.2Hz to accelerate the movement in stance-direction already in the late swing phase.

The SCORPION IV is able to move through various terrains (rock fields (with boulders up to 28cm diameter), asphalt, sand, gravel, grass). This was tested at several outdoor locations. The system can overcome by means of reflexes singular obstacles (perpendicular to the ground) of up to 30cm height (8 cm more than its ground clearance). Non singular obstacles like rubble piles can be overcome, if the variance in this rubble pile does not exceed this maximum possible height change.

The system is able to safely walk up an inclination of 35° while overcoming smaller obstacles of 10cm height. For steeper slopes a special coordination pattern can be used which moves one leg after the other forward before all legs stance together. This allows depending on the ground to move up slopes of 45° on the cost of speed. For these experiments the standard rubber feet of the SCORPION have been used, still better climbing abilities are likely to be achieved, if special designed feet would be developed.



Fig. 20. SCORPION Robot using the PCR approach to climb along a beam

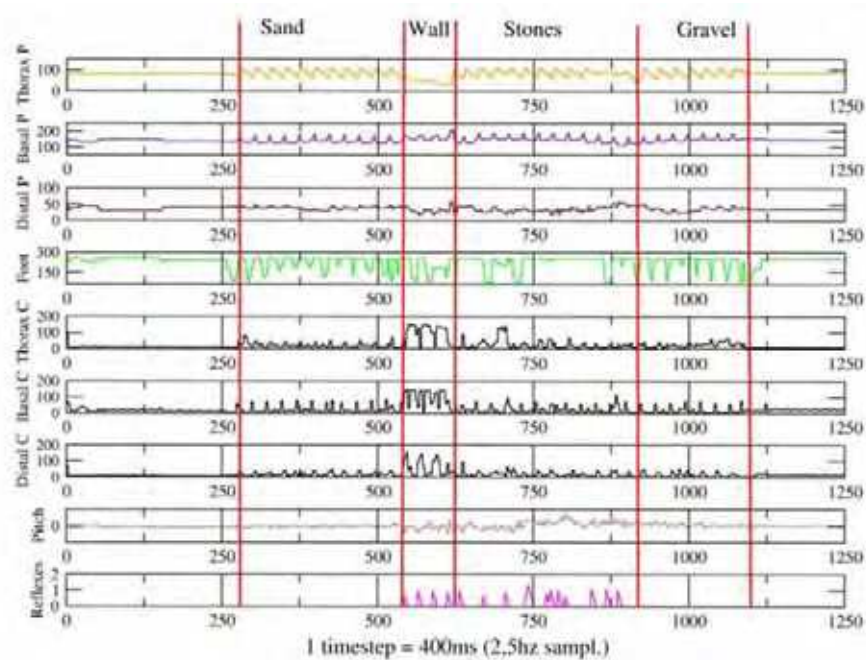


Fig. 21. Data from the left foremost leg in a run through a test-bed consisting of a sand part, a stone wall, a rock-field, and a gravel field. Line 1-3: real joint angle values, line 4 footpressure sensor data, line 5-7: current values, line 8: pitch value of the body, line 9: value for reflex occurrences.

These results have been obtained from tests in the locomotion lab of the University of Bremen as well as at the South West Research Institute in San Antonio in Texas.

Furthermore, we have proven that the control approach could not only be used for locomotion but for other movements, like climbing along a beam (see Fig.) or manipulating objects, too. This is primarily done by combining the standard CPGs with a totally different basic posture. To climb along a beam, for example, is achieved by activating the forward walking pattern for the foremost and hindmost legs and by using a posture where the robot sticks to the beam.

Based on these results, we can argue that the PCR-approach is a very flexible and efficient tool for programming new locomotion behaviours and that SCORPION IV is a very robust walking robot.

Because of the clear distinction between rhythmic control, posture control, and reflex control necessary adaptation to an existing programme can be done with low effort, which make this approach suitable for bottom up programming. The introduction of motoric programmes supports also this modularization for high reusability.

On the other hand we also experienced that the PCR-approach is sub-optimal for the production of energy-optimized trajectories. Here, model-based approaches could provide better solutions. But they would need very accurate modelling of the environment to achieve this theoretically possible better performance. Therefore, better sensors and high computational power would be needed, which are not available yet and would make such systems tremendously expensive.

Another approach for the modelling of the environment might be to use the proprioceptive data of the walking robots for terrain classification to enhance the information gained by exteroceptive sensors. To test this, a self-growing neural network approach - growing cell structures - was used to distinguish between different substrates. An example of the used proprioceptive data is shown in Fig.. The classifier was able to distinguish three groups: a) gravel/sand, b) the wall, and c) the rock-field(stones) from each other by using this data as input values. More details can be found in (Spenneberg & Kirchner (2005c).

4. Conclusions

The PCR-approach showed that it is possible to define models for the low-level biological motoric concepts and combine them, so that they can be used with a behaviour-based control approach in a flexible way. The control of the posture, while the system is walking, gives additional flexibility in comparison to the CCPG approach (Ayers 2002) or the Walknet approach (Cruse 1999).

In addition, the combination of different walking patterns, e.g., for an omni-directional movement, produces a rich motion repertoire on the basis of a small set of elementary locomotion patterns which are defined with few parameters.

But, recapitulating, none of the existing bio-inspired approaches including the PCR-approach yet is able to use the full motion potentials which walking robots have.

Especially in very complex environments, e.g. steep slopes or the earlier mentioned random stepping fields, these reactive approaches show their limits. On the other hand, these are the environments, where the, in principle, higher mobility of ambulating systems in comparison to wheeled or tracked systems, would pay off.

One way for the future will be the combination of the bio-inspired approaches with approaches to model the environment plus the robot and to plan steps before their execution. But, as we have already discussed such an approach would need to work firstly on a correct model and secondly would have to be based on very accurate motion execution. The problem of 3D-world-modelling and kinematical modelling in real time has yet to be solved before this path becomes an option

Perhaps, regarding this issue it is reasonable to get inspired again by the research on biological systems.

They seem to use such complex world models only seldom, especially if we study invertebrates. One explanation why these systems can nonetheless operate in such difficult environments, is that their extremely high number of acquired sensory information and the high number of corresponding sensomotoric feedback loops plays a crucial role in the motion adaptation.

For example, the legs of insects are covered with thousands of partly specialized sensors. Thus, these systems are much more embedded into the world than our robots. Biological systems in comparison to the robots are fully situated in the world and hence can still cope in the mentioned environments without complex internal world-models. We believe that they can use this sensory information to locally model and classify their environment very accurately, the experiment described above for the terrain classification is a first hint in this direction.

Due to this hypothesis, we see one of the major challenges for robotics to close this sensorial gap by advancing the mechatronical design and the integration of a multitude of sensors into the material of our robotic systems, e.g. developing a leg which is made by "intelligent aluminium" which already contains hundreds of pressure sensors. This provides us with a second challenge: To find suitable algorithms and concepts to process these signals in parallel. In addition, the design of these walking robots can be improved by developing a self-adapting "intelligent morphology" which requires still less control to produce terrain-suited locomotion patterns. Here especially the ongoing work on passive walkers and elastic actuation looks very promising with view to the future.

5. References

- Albrecht M.; Backhaus T.; Planthaber S.; Stoeppler H.; Spenneberg D.; & Kirchner F. (2005) Aimee: A four-legged robot for robocup rescue. In *Proceedings of CLAWAR 2005*. Springer, 2005.
- Ayers, J. (2002). A conservative biomimetic control architecture for autonomous underwater robots. In Ayers, Davis, and Rudolph, editors, *Neurotechnology for Biomimetic Robots*, pages 241--260. MIT Press, 2002.
- Beer, R.D; Quinn R.D. ; Chiel, H.J ; & Ritzmann, R.E. (1997). Biologically-inspired approaches to robotics. In *Communications of the ACM*, 40(3):30–38, 1997.
- Bowerman, R.F. (1975). The control of walking in the SCORPION - I. leg movements during normal walking. In *Journal of Comparative Physiology*, 100:1 183--196, 1975.
- Cruse, H; Dean, J; Kindermann D.; Schmitz J., & Schumm, M. (1999). Walknet - a decentralized architecture for the control of walking behaviour-based on insect studies. In G.Palm, editor, *Hybrid Information Processing in Adaptive Autonomous Vehicles*. Springer, 1999.

- Gaßmann, B.; Scholl, K. U.; & Berns, K (2001). Behaviour control of Lauron III for walking in unstructured terrain. In *Proceedings of CLAWAR 2001*, pages 651--658, 2001.
- Go, Y.; Yin, X.; & Bowling A. (2005) Navigability of multi-legged robots. In *IEEE/ASME Transactions on Mechatronics*, 2005.
- Ijspeert A.J.; Crespi A. ; & Cabelguen J.M. (2005) Simulation and robotics studies of salamander locomotion. Applying neurobiological principles to the control of locomotion in robots. In *Neuroinformatics*, 3 (3):0 171--196, 2005.
- Kirchner, F. (1998) Q-learning for complex behaviours on a six-legged walking machine. In *Journal of Robotics and Autonomous Systems*, 25, 256--263, 1998.
- Kirchner, F. ; Spenneberg, D. & Linnemann. R. (2002) A biologically inspired approach towards robust real world locomotion in an 8-legged robot. In J.Ayers, J.Davis, and A.Rudolph, editors, *Neurotechnology for Biomimetic Robots*. MIT-Press, Cambridge, MA, USA, 2002.
- Löffler, K; Gienger K.; & Pfeiffer F. (2003) Sensor and control design of a dynamically stable biped robot. In *Proc. of the International Conference on Robotics and Automation 2003*, pages 484--490, 2003.
- Maes P.; & Brooks R.A. (1990). Learning to coordinate behaviours. In *National Conference on Artificial Intelligence*, pages 796--802, 1990.
- Reichert, H. (1993) *Introduction to Neurobiology* (book). Thieme, 1993.
- Spenneberg, D.; & Kirchner, F. (2000) Omnidirectional walking in an eight legged robot. In *Proceedings of the 2nd Int. Symposium on Robotics and Automation (ISRA2000)*, Monterrey, N.L., Mexico, 2000.
- Spenneberg, D.; & Kirchner, F. (2001) An approach towards autonomous outdoor walking robots. In *Proceedings of the 10th Int. Conf. on Advanced Robotics (ICAR 2001)*, Budapest, Ungarn, 2001.
- Spenneberg D.; Kirchner F. & de Gea, J.(2004). Ambulating robots for exploration in rough terrain on future extraterrestrial missions. In *Proceedings of the 8th ESA Workshop on Advanced Space Technologies for Robotics and Automation (ASTRA 2004)*. European Space Agency, November 2004
- Spenneberg D. (2005a). A hybrid locomotion control approach. In *Proceedings of the CLAWAR 2005 Conference*, September 2005.
- Spenneberg, D. ; Albrecht, M.; Backhaus, T. (2005b) M.o.n.s.t.e.r.: A new behaviour-based microkernel for mobile robots. In *Proceedings of the ECMR 2005*, September 2005.
- Spenneberg, D. ; & Kirchner, F. (2005c) Learning spatial categories on the basis of proprioceptive data. In *Proceedings of the 3rd International Symposium on Adaptive Motion in Animals and Machines*, September 2005
- Wilson, D.M (1961) The central nervous control of flight in a locust. In *Journal of Experimental Biology*, 38: 471--490, 1961.



Climbing and Walking Robots: towards New Applications

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With the advancement of technology, new exciting approaches enable us to render mobile robotic systems more versatile, robust and cost-efficient. Some researchers combine climbing and walking techniques with a modular approach, a reconfigurable approach, or a swarm approach to realize novel prototypes as flexible mobile robotic platforms featuring all necessary locomotion capabilities. The purpose of this book is to provide an overview of the latest wide-range achievements in climbing and walking robotic technology to researchers, scientists, and engineers throughout the world. Different aspects including control simulation, locomotion realization, methodology, and system integration are presented from the scientific and from the technical point of view. This book consists of two main parts, one dealing with walking robots, the second with climbing robots. The content is also grouped by theoretical research and applicative realization. Every chapter offers a considerable amount of interesting and useful information.

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