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A Behaviour Network Concept for Controlling Walking Machines*

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Abstract

The high complexity of the mechanical system and the difficult task of walking itself makes the task of designing the control for legged robots a diffcult one. Even if the implementation of parts of the desired functionality, like posture control or basic swing/stance movement, can be solved by the usage of classical engeneering approaches, the control of the overall system tends to be very unflexible. This paper introduces a new method to combine apects of classical robot control and behaviour based control. Inspired by the activation patterns in the brain and the spinal cord of animals we propose a behaviour network architecture using special signals like activity or target rating to influencce and coordinate the behaviours. The general concept of a single behaviour as well as their interaction within the network is described. This architecture is tested on the four-legged walking machine BISAM and experimental results are presented.

keywords: Four-Legged Walking Machine, Behaviour Based Control

1. Introduction

Walking robots have been a field of increasing activity in the last years. Especially the ability to adapt to unstructured terrain and the resulting demands on the control architecture have been in the focus of researchers. These efforts can be separated into two different approaches, one being the classical engineering approach using and refining the known methods of loop-back control structures and dynamic modelling to control the robot, e.g. [Gienger 01]. The other way is to adopt as much from biological paragons for locomation as possible regarding both mechanical design and control architecture, e.g. [Ayers 00b] and [Kimura 01] . The methods proposed in this paper follow the second approach by applying a reflex or behaviour based control architecture to a four-legged walking machine, this way performing sensor-based adaptation to motion on irregular terrain.

Biological research of the last years has identified several key elements being used in nature for adapting locomotion. These range from the geometrical structure of legs [Witte 01] and dynamic properties of muscles [Pearson 95] to neural networks used for walking by insects [Cruse 95] and [Cruse 01]. The results of this research suggest a transfer of these principles to legged robots. Due to the high complexity of real walking machines and the impracticality of mimicking especially nature's activators and sensors, up to now only some of the ideas have been transferred to the control architectures of real robots. In [Kimura 00] and [Kimura 01] a neuro-oscillator based pattern generator is introduced. The adaptation to the terrain is solved by directly influencing the activation of the oscillator neurons. [Ayers 00a] also uses neuro-oscillators which are parametrized using the results from the analysis of lobsters. [Hosoda 00] proposes a reflex based gait generation system, triggered by the input of a camera system mounted on the robot. A distributed control system for a hexapod using reflexes to stabilize the body is presented in [Espenschied 96].

In the last years several methods were successfully applied to control the four-legged walking machine BISAM [Berns 98]. These include the usage of coupled neuro-oscillators for gait generation [Ilg 98a], learning leg trajectories [Ilg 98c] and the application of radial basis function neural networks and reinforcement learning methods for posture control while trotting [Ilg 01] and [Albiez 01]. All these methods were successfull but lacked a certain extensibility when confronted with more demands than they were initially designed for (e.g. both dynamically stable trott and statically stable walking). Thus the necessity arrised to build an architecture being able to handle these demands.

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2. Activation, Activity, Target Rating and Behaviours

There have been several approaches to use behaviour based control in mobile robots over the last years. The main area of application have been wheel driven, kinematically extremly simple robots, with the main focus on the robot's task eg. navigation and group behaviour (see [Endo 01],[Arkin 00b] and [Mataric 97]). Therefore these architectures concentrate on the coordination of a set of high level behaviours operating mostly on the same semantic level and producing abstract commands for the robot's hardware. Since the coordaintion of behaviours is crucial part in behaviour based robotics a lot of work has been done there. Examples include comfort zones [Likhachev 00] or case based reasoning [Likhachev 01]; a good overview on behaviour coordination can be found in [Pirajanian 99].

There have only been a few attempts to use behaviour based architectures on the lower levels of the control architecture for kinematically more complex robots like walking machines. The best known and most successful is the subsumption architecture [Brooks 86], [Ferrell 95] used on several hexapods. A more biological inspired approach for a lobster robot is proposed in [Ayers 00b]. But there are several drawbacks to these architectures, among them a general tendency towards scalability problems, weaknesses when adding new behaviours or trying reusing existing ones and in most cases a highly problem specific approach (see [Arkin 00a]).

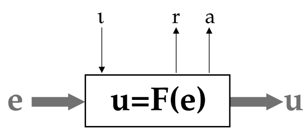

Figure 1: Behaviour design

When considering the insights gained through PET and EEG scans and spinal cord activity plots of animals performing certain tasks ([Kandel 00] and [Pearson 95]), as well as the problems when dealing with real sensor information and highly complex robots, the following key aspects can be identified:

- A certain action of an animal always creates activity in the same area of the animal's brain or its spinal cord.
- Such an active area can result in the stimulation of further regions as well as inhibit activity in others.
- Even though the classical approach to robot control has difficulties handling the complexity of the whole system, these established methods should be applied to solve simpler sub-problems.
- As hierarchical systems have been approved in robotics as well as in nature it is advisable to use some kind of leveled system with an increasing degree of abstraction regarding sensor data and motor signals.

Taking these observation into consideration, we designed a control architecture consisting of a hierarchical network of behaviours. Each behaviour or reflex[1] is developed using methods of classical control system design or artificial intelligence. Only the interaction of the behaviours and their placement in the network will result in the desired actions of the overall system.

Each such behaviour $\mathcal{B}$ as used in this architecture can formally be defined as

$$\mathcal{B} = (\vec{e}, \vec{u}, \iota, F, r, a).$$

This functional unit uses the input vector $\vec{e}$ and generates the output vector $\vec{u}$. It possesses another dedicated input value ι to activate the behaviour on a scale between 0 (disabled) and 1 (fully activated). This allows to ensure the robot's safety to a certain degree by activating only a defined set of behaviours and enables the usage of the behaviour as an abstract actor by other higher level behaviours. The transfer function F can then be defined as

$$F : \Re^n \times [0;1] \to \Re^m; \qquad F(\vec{e}, \iota) = \vec{u}.$$

Each behaviour generates two further output values, the target rating r and the activity a. These are set apart from the control output $\vec{u}$ as they are not used for control purposes but more treated as kind of sensor information about the behaviour's state. The target rating r evaluates the system state from the restricted view $\vec{e}$ of the behaviour.

$$r : \Re^n \to [0;1]; r(\vec{e}) = r$$

It is constantly calculated even if the behaviour is deactivated and generates no output. A value of 0 indicates that the robot's state matches the behaviour's goal, a value of 1 that it does not. The activity a reflects the magnitude of the behaviours action:

$$a : \Re^m \to [0;1] : a(\vec{u}) \sim ||\vec{u}||$$

[1] A reflex refers to a simple behaviour close to the hardware thus being more reactive than deliberative

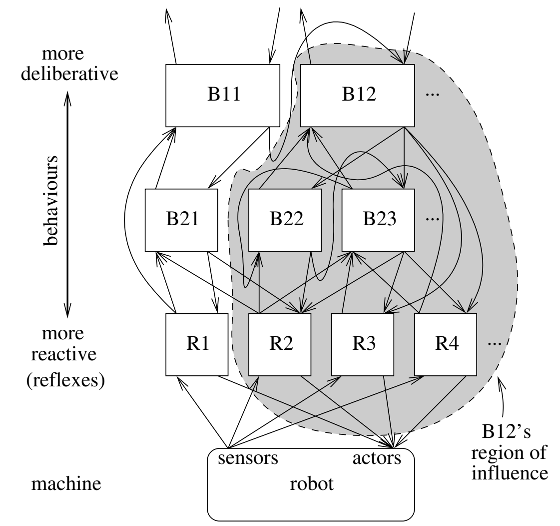

Figure 2: Behaviour coordination network

Apart from giving crucial visualisable information for the control system developer, ι, r and a are responsible for the interaction between the behaviours within the network. The network itself is a hierachical distribution of the behaviours according to their functionality. The more reflex-like a behaviour is the lower it is placed inside the network (see figure 2). Higher behaviours are using the functionality of lower ones via their ι inputs like these could be using motor signals to generate robot movement. From this activation mechanism emerge the regions of influence $\mathcal{R}$ as shown in figure 2 which are recursively defined as

$$\mathcal{R}(B) = \bigcup_{B_i \in Act(B)} \{B_i \cup \mathcal{R}(B_i)\},$$

$$\mathcal{R}(B) = \emptyset, \quad \text{if} \quad Act(B) = \emptyset,$$

where $Act(B)$ is the set of behaviours being influenced by $\mathcal{B}$ via ι. This affiliation of a behaviour to a region is not exclusive, it only expresses its cooperation with other behaviours. The activity of the complete network will concentrate in the region of one high level behaviour.

The state variables a and r are used to pass information about a behaviour to others. The target rating r hints on the behaviour's estimation of the situation whereas the activity a describes how much it is working on changing this situation thus influencing other behaviours decisions and actions.

The activity also acts as a mean for the fusion of the outputs of competing behaviours (see figure 3). Either only the output of the behaviour with the highest activity (winner takes it all) is used or the average of all outputs weighted by the activities is calculated.

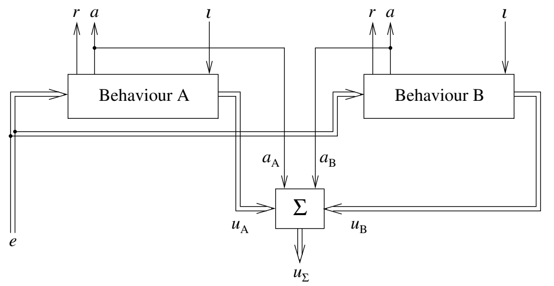

Figure 3: Fusion of different behaviours outputs using their activation as weighting criterion.

3. The Walking Machine BISAM

BISAM (Biologically InSpired wAlking Machine), developed ath the FZI, consists of one main body and four equal legs (figure 4). The main body is com-

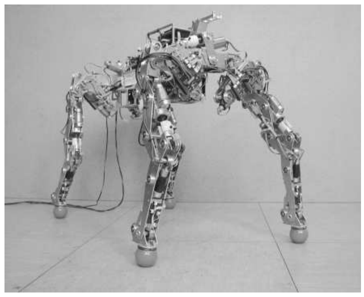

Figure 4: The quadrupedal walking machine BISAM. Due to the five active degrees of freedom in the body and the ability to rotate the shoulder and hip, BISAM implements key elements of mammal-like locomotion.

posed of four segments being connected by five rotary joints. Each leg consists of four segments connected by three parallel rotary joints and attached to the body by a fourth. The joints are all driven by DC motors and ball screw gears. The height of the robot is 70 cm, its weight is about 23 kg. 21 joint angle encoders, four three dimensional foot sensors and two inclinometers mounted on the central body provide the necessary sensoric input. A more detailed description of the development and specification of BISAM can be found in [Berns 99] and [Ilg 98b]. Research on BISAM aims at the implementation of mammal-like movement and different gaits like statically stable walking and dynamic trotting with continuous gait transitions. Due to this target, BISAM is developed with joints in the shoulder and in the hip, a mammal-like leg-construction and small foot contact areas. These features have strong impact on the appliable methods for measuring stability and control. For example, caused by BISAM's small feet the ZMP-

Criterion [Vukobratovic 90] is not fully adequate to describe the aspired movements.

The control design has to consider the high number of 21 active joints and especially the five joints in the body. One common way to reduce the model complexity is to combine joints and legs by the approach of the virtual leg, as used in many walking machines [Raibert 86], [Kimura 90], [Yoneda 92]. This approach poses problems when modelling BISAM's body joints and lead to a strong reduction in the flexibility of the walking behaviour [Matsumoto 00]. A second way is to reduce the mechanical complexity of the robot so it is possible to create an exact mathematical model of the robot [Buehler 99].

Taking the described problems into consideration BISAM was used as the first plattform to implement the proposed behaviour based architecture ([Albiez 02c] [Albiez 02a] [Albiez 02b]). This first implementation has been expanded to a complete and consistent framework, which allows BISAM to automatically switch between standing, a free gait and a normal walking gait.

4. Implementing a Behaviour Network

Up to now we have implemented a behaviour network for BISAM which realises stable standing and a free gait. The sub-network controlling one leg is shown in figure 5. Note that the stance behaviour is inhibited by the swing behaviour via the activity to guarantee that stancing will stop as soon as the leg is cleared for swinging. The two "helper" behaviours, preparing a swing phase and keeping the ground contact, are the most reactive in this group and as such are placed at the bottom.

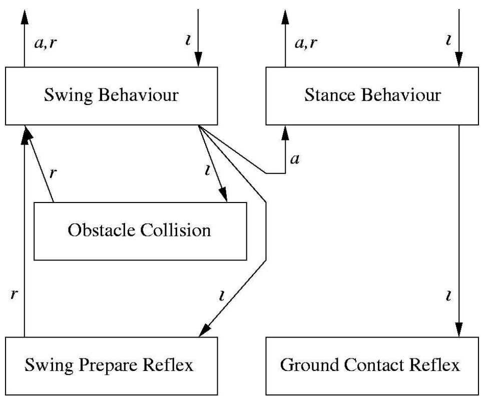

Figure 5: Behaviour network for one leg

The overall network of BISAM is shown in figure 6. For clarity reasons the networks of the legs are only shown as blocks, since they operate independent from each other. Above them reside the posture behaviours as described in ([Albiez 02c]). The walking behaviours on the highest level only activate lower behaviours and don't generate direct control signals at all. The fusion knots between the walking and the posture behaviours guarantee that only the output of the active walking behaviour is used. The transition between standing and different gaits is done by the walking behaviours themselves.

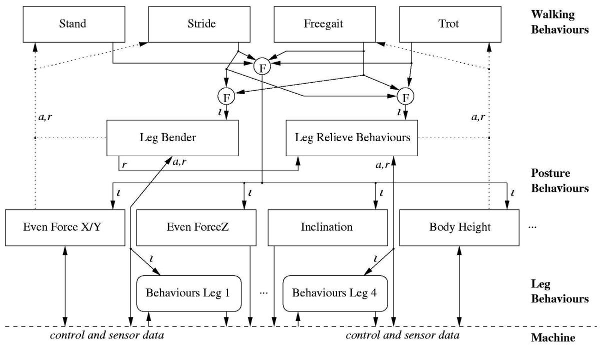

Figure 6: Behaviour network of the complete robot

To demonstrate the activities and the coordination of the bahaviours a simple step on even terrain as performed in free gait is described here. In figure 7 the swing phase of the leg is represented by its x-coordinate (uppermost plot) and several involved behaviours are visualized by their activation ι, activity a and target rating r (top-down). All behaviour plots scale from 0 to 1. Not all behaviours involved in actual walking are described here but are ignored for reasons of simplicity.

Between two swing cycles the free gait will try to stabilize the robot on four legs while adapting the posture to the terrain. The force distributing reflex (first behaviour in figure 7) represents the posture control being activated after the swing leg hits the ground (high ι). At once its activity increases, the posture of the robot is corrected, so the target rating descreases accordingly.

At the beginning of a new swing cycles the leg relieve behaviour is activated. It tries to remove most of the weight from the selected swing leg by shifting the robot's posture. The better the relieve situation of the swing leg is rated, the more the swing behaviour is activated. As soon as the swing behaviour decides to start swinging, its activity increases, the leg is lifted from the ground. Simultaneously the stace behaviour

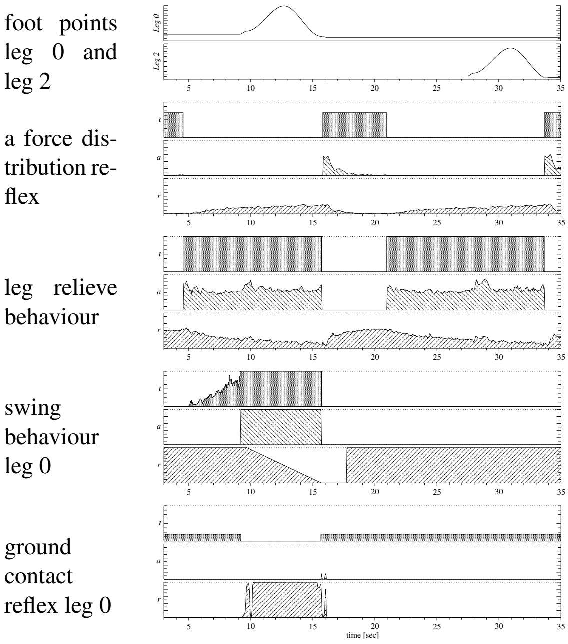

Figure 7: Some of the behaviours involved while walking on even terrain in free gait

is inhibited which will no longer activate the ground contact reflex (bottom-most plot in figure 7). The target rating of the ground contact reflex will shoot up as soon as the leg leaves the ground, but the relfex cannot change the situation as it is not activated; its acitivity a remains Zero.

It is to be noted here that walking on unstructured terrain won't differ greatly from the situation above. The main differnce will be some more activity of the posture reflexes, the swing and stance mechanisms remain the same. Obstacles are hidden from them by the posture control and the collision reflex.

5. Conclusion and Outlook

This paper introduced an hierarchical activation based behaviour architecture. Three dedicated signals, the activity a, the activation ι and the target rating r are used to coordinate the interaction of behaviours within the network. Such a network for stable standing and a free gait was successfully implemented for a complex four-legged walking robot. Future work will mainly consist of the design and testing of different gait transition schemes and the integration of more sensors to allow anticipatory activation of the behaviours on BISAM. Furthermore there is ongoing work on using this architecture on other Robot's of FZI, namely the six-legged walking machines AirBug and Lauron III and the new four-legged Panter.

References

[Albiez 01] J. Albiez, W. Ilg, T. Luksch, K. Berns, R. Dillmann. Learning reactive Posture Control on the four-legged Walking machine BISAM. In *International Conference on Intelligent Robots and Systems (IROS)*, Hawaii, USA, November 2001.

[Albiez 02a] J. Albiez, T. Luksch, K. Berns, R. Dillmann. An Activation Based Behaviour Control Architecture for Walking Machines. In *Proceedings of the 7th International Conference on Simulation of Adaptive Behaviour SAB*, Edingburgh, UK, August 2002.

[Albiez 02b] J. Albiez, T. Luksch, K. Berns, R. Dillmann. Hierachical Activation-based Behaviour Architecture for a four-legged Walking Machine. In *Proceedings of the 5th International Conference on Climbing and Walking Robots CLAWAR*, Paris, France, September 2002.

[Albiez 02c] J. Albiez, T. Luksch, W. Ilg, K. Berns, R. Dillmann. Reactive Reflex Based Control for a Four-Legged Walking Machine. In *Proceedings of the 7th International Conference on Inteligent Autonomous Systems IAS*, Los Angeles, California, USA, March 2002.

[Arkin 00a] R. Arkin. *Behavior-Based Robotics*. MIT Press, 2000.

[Arkin 00b] R. Arkin, A. Kahled, A. Weitzenfeld, F. Cervantes-Prez. Behavioral models of the Praying Mantis as a basis for robotic behavior. *Journal of Autonomous Systems*, 2000.

[Ayers 00a] J. Ayers, J. Witting, C. Olcott, N. McGruer, D. Massa. Lobster Robots. In T. Wu, N. Kato (Hrsg.), *Proceedings of the International Symposium on Aqua Biomechanisms*, 2000.

[Ayers 00b] J. Ayers, J. Witting, C. Wilbur, P. Zavracky, N. McGruer, D. Massa. Biomimetic Robots for Shallow Water Mine Countermeasures. In *Proc. of the Autonomous Vehicles in Mine Countermeasures Symposium*, 2000.

[Berns 98] K. Berns, W. Ilg, M. Eckert, R. Dillmann. Mechanical construction and computer architecture of the four-legged walking machine BISAM. In *CLAWAR '98 - First International Symposium*, S. 167–172, 1998.

[Berns 99] K. Berns, W. Ilg, M. Deck, J. Albiez, R. Dillmann. Mechanical Construction and Computer Architecture of the four-legged Walking Machine BISAM. *IEEE Transactions on Mechatronics*, 4(1):1–7, Mrz 1999.

[Brooks 86] R.A. Brooks. A Robust Layered Control System for a Mobile Robot. *IEEE Journal of Robotics and Automation*, RA-2(1):14–23, April 1986.

[Buehler 99] M. Buehler, A. Cocosco, K. Yamazaki, R. Battaglia. Stable Open Loop Walking in Quadruped Robots with Stick Legs. In *Proceedings of the IEEE International Conference on Robotics and Automation*, S. 2348–2354, Detroit, Mai 1999.

[Cruse 01] H. Cruse, V. Drr, J. Schmitz. Control of a hexapod walking - a decentralized solution based on biological data. In *Proc. of the 4th International Conference on Climbing and Walking Robots (CLAWAR)*, Karlsruhe, Germany, September 2001.

[Cruse 95] H. Cruse, C. Bartling. Movement of joint angles in the legs of a walking insect, Carausius morosus. *J. Insect Physiol.*, (41):761–771, 1995.

[Endo 01] Y. Endo, R. Arkin. Implementing Tolman's Schematic Sowbug: Behaviour-Based Robotics in the 1930's. In *Proceedings of the 2001 IEEE International Conference on Robotics and Autonomous Systems*, 2001.

[Espenschied 96] K. Espenschied, R Quinn, H. Chiel, R. Beer. Biologically-based distributed control and local reflexes to improve rough terrain locomotion in a hexapod robot. *Robotics and Autonomous Systems*, 18:59–64, 1996.

[Ferrell 95] C. Ferrell. Global Behavior via Cooperative Local Control, S. 105 – 125, 1995.

[Gienger 01] M. Gienger, K. Lffler, F. Pfeiffer. In *Proc. of the IEEE International Conference on Robotics and Automation (ICRA)*, 2001.

[Hosoda 00] K. Hosoda, T. Miyashita, M. Asada. Emergence of Quadruped walk by a Combination of Reflexes. In *Procceedings of the International Symposium on adaptive Motion of Animals and Machines*, Montreal, August 2000.

[Ilg 01] W. Ilg. *Eine biologisch motivierte adaptive Bewegungssteuerung fr eine vierbeinige Laufmaschine*. Infix-Verlag, 2001. Dissertationsschrift (in german).

[Ilg 98a] W. Ilg, J. Albiez, H. Jedele. A Biologically Inspired Adaptive Control Architecture Based on Neural Networks for a Four-Legged Walking Machine. In *Proceedings of the 8th International Conference on Artificial Neural Networks*, S. 455–460, Skoevde, September 1998.

[Ilg 98b] W. Ilg, K. Berns, H. Jedele, J. Albiez, R. Dillmann, M. Fischer, H. Witte, J. Biltzinger, R. Lehmann, N. Schilling. BISAM: From Small Mammals to a Four Legged Walking Machine. In *Proceedings of the Fifth International Conference on Simulation of Adaptive Behaviour*, S. 400–407, Zrich, August 1998.

[Ilg 98c] W. Ilg, K.-U. Scholl. CQRAN: Continuous Q-Learning Resource Allocation Network. Towards reinforcement Learning with multi-dimensional continuous action spaces. In *Proceedings of the 8th International Conference on Artificial Neural Networks, Skoevde, Sweden*, S. 455–460, Skoevde, September 1998.

[Kandel 00] E.R. Kandel, J.H. Schwartz, T. M. Jessell. *Principles of Neural Science*. McGraw-Hill, Ausgabe 4th Ed., 2000.

[Kimura 00] H. Kimura, Y. Fukuoka. Biologically Inspired Dynamic Walking on Irregular Terrain - Adaptation at Spinal Cord and Brain Stem. In *International Symposium on Adaptive Motion of Animals and Machines*, Montreal, August 2000.

[Kimura 01] H. Kimura, Y. Fukuoka, Y. Hada, K. Takase. Three-dimensional adpative dynamic walking of a quadruped robot by using neural system model. In *Proc. of the 4th International Conference on Climbing and Walking Robots (CLAWAR)*, Karlsruhe, September 2001. FZI.

[Kimura 90] H. Kimura, I. Shimoyama, H. Miura. Dynamics in the Dynamic Walk of a Quadruped Robot. *Advanced Robotics*, 4(3):283–301, 1990.

[Likhachev 00] M. Likhachev, R. Arkin. Robotic Comfort Zones. In *Proceedings of the SPIE: Sensor Fusion and Decentralized Control in Robotic Systems*, S. 27–41, 2000.

[Likhachev 01] M. Likhachev, R. Arkin. Spatio-Temporal Case-Based Reasoning for Behavioral Selection. In *Proceedings of the 2001 IEEE International Conference on Robotics and Automation (ICRA)*, S. 1627–1634, 2001.

[Mataric 97] Maja J. Mataric. Behavior-Based Control: Examples from Navigation, Learning, and Group Behavior. *Journal of Experimental and Theoretical Artificial Intelligence*, Special issue on Software Architectures for Physical Agents, 9(2-3):323–336, 1997.

[Matsumoto 00] O. Matsumoto, W. Ilg, K. Berns, R. Dillmann. Dynamical Stable Control of the Four-legged Walking Machine Bisam in Trot Motion Using Force Sensors. In *Intelligent Autonomous Systems 6*, 2000.

[Pearson 95] K.G. Pearson. Proprioceptive Regulation of Locomotion. *Current Opinions in Neurobiology*, 5(6):768–791, 1995.

[Pirajanian 99] P. Pirajanian. Behaviour Coordination Mechanisms - State-of-the-art. Technischer Bericht IRIS-99-375, Institute for Robotics and Intelligent Systems, School of Engineering, University of Southern California, 1999.

[Raibert 86] Marc H. Raibert. *Legged Robots That Balance*. MIT Press, Cambridge, MA, 1986.

[Vukobratovic 90] M. Vukobratovic, B. Borovac, D. Surla, D. Stokic. *Biped Locomotion*. Springer–Verlag, Heidelberg, Berlin, New York, 1990.

[Witte 01] H. Witte, R. Hackert, K. Lilje, N. Schilling, D. Voges, G. Klauer, W. Ilg, J. Albiez, A. Seyfarth, D. Germann, M. Hiller, R. Dillmann, M.S. Fischer. Transfer of Biological Priciples into the Construction of Quadruped Walking Machines. In *Second International Workshop On Robot Motion And Control*, Bukowy Dworek, Poland, 2001.

[Yoneda 92] K. Yoneda, S. Hirose. Dynamic and Static Fusion Gait of a Quadruped Walking Vehicle on a Winding Path. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, S. 143–148, Nizza, Mai 1992.