Biological Motivated Control Architecture and Mechatronics for a Human-Like Robot

Thomas Wahl, Sebastian Blank, Tobias Luksch, and Karsten Berns

Abstract. In this paper the lower levels of a biological inspired control architecture for dynamically moving legged robots are presented. This architecture features a hierarchical distributed reflex based high level controller as well as the possibility to adjust the compliance of a stiff actuated joint. Furthermore the respective mechatronical setup for that approach is presented, that includes the actuation and energy storage in parallel springs. The approach is verified on a prototype leg mounted on a vertical slider, that is capable of performing a cyclic squat jump. The reflex based control concept is tested in a physics simulation environment. The experimental validation shows that no series elastic elements are required to receive comparable results with respect to the resulting motion. The low level stiffness controller is implemented on a DSP-board and tested using an experimental setup with two motors.

1 Introduction

Bipedal locomotion has been a field of high interest in robotics during the last decades. This is among other things due to the fact that human environment favors this kind of locomotion over e.g. wheel based approaches. If mastered it offers highly versatile and energy efficient movements that will allow the robot to advance into areas that were not accessible to machines in the past.

Amongst the important aspects of a bipedal robot is a sound concept concerning mechantronics and control aspects. The biological representatives of two-legged locomotion show high energy efficiency and the ability to adapt to external disturbances compared to state-of-the-art technical implementations. Thus, biological

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mechanisms seem to be promising as a guideline for the design process without trying to copy them but rather make use of nature's concepts. The short-term goal is to deduce a system including mechanics, a reflex-based control architecture and a suited actuator control approach that can be used in a walking machine later on.

To evaluate these basic concepts, the work presented here advances a single leg prototype with biological motivated joints and control from an earlier project[1] [15]. The demonstrator is to perform cyclic squat jumps stabilized in a vertical slider. This highly dynamic motion is a meaningful benchmark as it poses considerable demands on the mechatronics and the control system.

2 State of the Art

Contemporary bipedal robots can be classified into two major groups: On the one hand the robots with fixed trajectory planning and no compliance, e.g. ASIMO, LOLA [12] and on the other the robots with elastic actuation respectively passive elastic elements inspired by the passive walkers by Tad McGeer et al. [16]. Those ideas were employed in the actuated passive walkers by e.g. Collins et al. [5] and Anderson et al. [2]. The second group tries to adapt more biological principles. These principles are optimized by evolution for energy efficiency. Elastic actuated robots can be divided once more in two basic approaches to acquire compliance. The first one makes use of specialized hardware with elastic elements while the other realizes the desired behavior using software with compliant control techniques.

A representative for the hardware approach is the Series elastic actuator (SEA) [6, 19]. This method combines an inelastic actuator like DC motor or hydraulic actuator with a fixed elastic element. A drawback of SEAs is non-trivial control of the desired stiffness. Other approaches that control the stiffness independently from the position have to make use of more than one actuator. The mechanically adjustable compliance and controllable equilibrium's position actuator (MACCEPA) [7] uses two separate servos. One servo controls the position and the second servo controls the stiffness of the joint. The drawback of these approaches is that the energy of the second actuator is lost in respect to movement. The fluidic muscles [10] use the antagonistic principle as can be found in biology. The antagonistic principle makes use of the nonlinearity of the elastic elements. Unfortunately this increases the control overhead at the same time.

Their are two major approaches that use a software solution: Virtual Model Control [18] and Impedance Control Methods [1] . Common for all these approaches is a stiff and retardant actuator. Obligatory for a software solution is a very fast sensor-controller-actuator-loop. This is reachable by distributing the control architecture on different CPUs.

[1] The initial leg prototype has been developed within the program 'Bionik - Innovationen aus der Natur" of the German Federal Ministry of Education and Research (BMBF).

3 Concept

Based on these biological motivated aspects a system should have the following components:

- actuator that can deliver high torques
- gearbox that allows free swing of the legs
- parallel elastic elements to store energy
- no explicit series elastic elements
- controller to adjust the stiffness of the joints
- reflex layer based on neurological concept
- easy to distribute functional units
- distributed control components for enhanced scalability

3.1 Mechanical Design

In consideration of the fact that the biped performs highly dynamic movements, the delivery of high torques is recommended. These high torques could be produced by either pneumatic or hydraulic actuators as well as DC motors. Due to the autonomy of the system the DC motors are the preferred solution. Another important detail is the controllability of such actuators. The control of pneumatic actuators is highly nonlinear and the antagonistic principle requires a second actuator.

In the swing phase of a walking gait the robot should use its mechanical dynamics to save energy. Hence the gear ratio has to be low. That allows the joint to be non-retardant in comparison to the commonly used harmonic drives.

For the energy storage during the squat phase parallel springs are attached to each joint [4] . These springs may not be too heavy such that all the benefit is compensated by their weight. There are three suitable kinds of springs. Two of these are the mechanical linear and rotary springs. They are very light and easy to handle. The third option is a pneumatic spring: they are slightly heavier and have a nonlinear force response.

3.2 Joint Control

In a jumping sequence an elastic configuration is required to avoid hard impacts at touchdown. Besides that in normal walking gaits the leg should use the mechanical dynamics by just relaxing the joint. On the other hand the joint has to be very stiff when the leg is in the support phase. These cases are nearly impossible to control with passive series elastic elements. Due to that the joint controller adjusts the stiffness of the joint. To perform these highly dynamic tasks the controller is built up hierarchical. The innermost loop has to be a very fast current-controller. The current is directly correlated to the output-torque of the motor. The current measurement is the most difficult for that controller, because it has to be very fast and synchronized to the PWM.

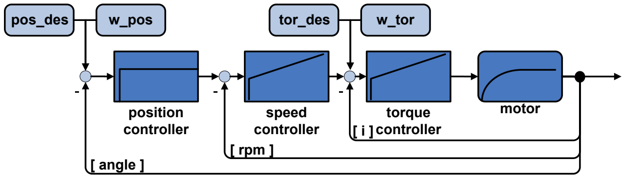


Fig. 1 Schematic view of the hierarchical closed loop controller.

Based on this current controller a speed and a position controller are implemented. A schematic layout and the interfaces of the controller are presented in Fig 1. The speed controller has no interface to the higher reflex layer. Biology shows that there is no need for an exact speed control. The desired position and torque impact of the controller output can be set using respective weight parameters named w_{pos} and w_{tor}. By decreasing w_{pos} the stiffness at a desired position is reduced. w_{tor} is proportional to the influence of a desired torque. This is e.g. the case during the pushoff phase: there is no need for an exact position since the maximum torque is required. In this phase w_{pos} is zero and w_{tor} is one with the maximum desired torque. To hold a fixed desired position w_{pos} is one and w_{tor} is zero.

3.3 Reflex Control

The joint control just mentioned presents the interface for the next layers of the control system. Complying with the biological motivation of this work, again concepts transferred from nature should be employed. The system described in the next paragraphs is based on a control approach for bipedal locomotion already published in more detail [14, 13].

Neurological control of cyclic motions seems to be a result of feedback and feedforward components. Bizzi, Ivanenko, and others have analyzed synergies of muscle activity during locomotion and suggest that the nervous system is of hierarchical layout [3, 11, 8, 9]. Based on the current phase of locomotion, coordinated patterns of activity are generated from a central unit and stimulate muscle groups to achieve the desired motion. Depending on this phase, reflex responses are modulated from spinal or supraspinal levels as well [21, 22].

Based on these and other results from biomechanics and neurology, the approach followed in this work suggests a hierarchical network of control modules to generate dynamic locomotion of legged robots. Control units are distributed and local to reduce the modelling effort and the complexity. Reflexes introduce a tight sensor/actor coupling for fast responses to stimuli and can be inhibited or modulated depending on the phase or mode of locomotion as it is the case in biological control. Motor patterns allow for temporal synergies of cooperating joints by generating synchronized torque impulses. No explicit joint trajectories are used so the natural system dynamics can be exploited and natural and energy-efficient motions emerge. Figure 2 illustrates the structure of the proposed approach. Skills represent control

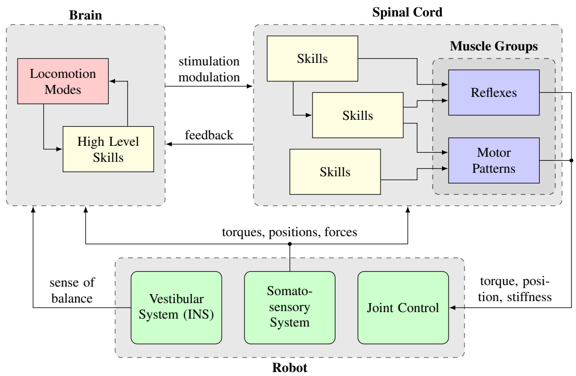


Fig. 2 The proposed control approach is structured as a hierarchical network of skill, reflexes and motor patterns.

units hierarchically above reflexes and motor patterns. The actual control components selected and designed to achieve the aspired motion are based on reflexes, muscle synergies and EMG data found in biological research and adapted to the technical system. The control network is implemented using a behavior-based control framework that was successfully used before on various robots by the authors and others and allows to implement the characteristics just mentioned [20].

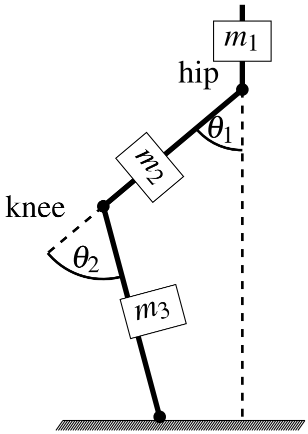
4 Prototype

4.1 System Description

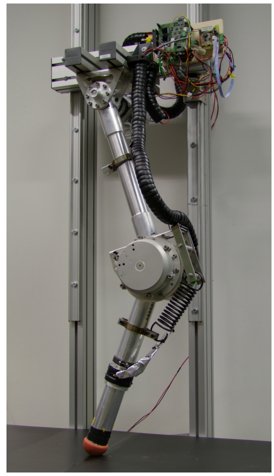
The single leg prototype is comprised of two actuated joints (hip, knee) and two limbs (thigh,shank). The hip joint is fixed to a vertical slider that allows for free movement in z-direction while restricting lateral change of position as well as rotation. In order to emulate the very sparse biological sensor concept the prototype is only equipped with two positional encoders located at each actuated joint and a load cell mounted in the middle of the lower limb. The construction is intended to be highly modular in order to be able to replace components or expand the kinematic setup with e.g. a passive foot construction. The dimension of the leg is human like. The height of the leg is nearly one meter and the weight is around 16 kg.

In order to acquire valid simulation results a dynamic model of the leg is needed to represent the actual one as closely as possible while allowing to introduce a few simplifications to reduce the computational overhead. Thus, the weight points assumed for each part are located in a position that represents the actual load distribution in the best possible way. The model is presented in figure 3(a).

The actuated joints consist of a DC motor, a gearbox with low gear ratio and parallel elastic elements. Finding a suited actuator for this kind of application is not an easy task since the restrictions in respect of dynamic properties can only be met



(a) Dynamic simulation model



(b) Photo of the prototype leg

Fig. 3 Schematic model used for simulation purposes (left) and a photograph of the prototype leg (right).

by very few actuators. A motor with a rotor disc seems to be ideal here since it offers very good dynamic properties due to its low inertia and high peak torque. The selected model offers a zero motion torque of approximately 13.72 Nm. Employing a gear ratio of 32 : 1 and neglecting the loss at the gearbox this would result in a maximum obtainable torque of 439 Nm. Unfortunately this can only be achieved for a very short time interval before the hardware would be destroyed due to a resulting current of more than 100 A. Thus, the sustainable peak torque is assumed to be 150 Nm for the simulation process.

4.2 Low Level Closed Loop Controller

The low level closed loop controller is implemented on a DSP-board. The DSP-board is connected via CAN-bus to the PC. Because of the encapsulation of the different reflexes there is no realtime capability required. The reflexes which need fast sensor informations, like touchdown reflex, can be directly implemented on the DSP.

The hip and the knee motor are connected to one DSP-board. For the speed and position measurement an optical-encoder is attached to the motor shaft. The encoders are connected via the CPLD to the DSP. The current measurement for each motor is realized by a shunt. Because of the non-continuous current due to the PWM the synchronisation of the measurement is a big problem. The solution is a timer that is synchronized in the DSP-hardware with the PWM and the AD-converter. The direction of the current is dedicated by the sign of the default PWM.

To reduce the noise of the measured current a simple lowpass-filter is implemented. The cycletime of the standard PI-controller is 1ms. That is fast enough to have an average risetime of about 8ms for a given desired current. This is concurrently the limiting setpoint setting of the speed controller and the desired torque. These two values are fusioned in a weighted sum (see equation 1). The fusion of the desired torque and the desired speed influences the stiffness of the joint. To avoid damage of the hardware the desired current is limited.

$$current_{des} = \frac{w_{pos}^2 * tor_{speed} + w_{tor}^2 * tor_{des}}{w_{pos} + w_{tor}} \quad (1)$$

The speed controller is also a classic PI-controller. The integral-portion is limited to avoid windup-effects when the weight of the position is very low. The third hierarchical controller is a position controller. Due to the integral portion of controlled system the position controller has no need for an integral portion. The acceleration of the speed controller is also limited. This is required to ensure the stability of the system (see [17]).

4.3 Reflex Control for Jumping

The jump is controlled by units on both the spinal cord and the muscle level. The spinal cord is the coordinating instance while the reflexes on the muscle level generate the actual commands for the joint controllers. The functionality on the spinal cord level is achieved through a behavior based module that acts as finite state machine (FSM) while the four reflexes are closely coupled with the hardware (see figure 4).

The Push off Reflex is intended to start in a squatted position that is reached using either the spinal cord level function to initialize the jump or the squat reflex during repetitive jumping. Once the reflex is stimulated, the leg is stretch out by applying torque to either actuated joints. Experiments have shown that the naive approve of applying the maximum momentum at both joints is contraindicated by the fact that this would cause undesired lateral force due to the closed kinematic chain of the leg. Thus the hip is relaxed almost entirely while the main share of the work is performed by the knee actuator. Torque is applied until leg remains slightly bend and is the entirely withdrawn to reduce the lateral movement in negative x-axis direction after the liftoff. Besides eliminating undesired movement this also helps to reduce the energy consumption of a jump motion. Once the foot point loses contact to the ground the activity of the reflex is withdrawn by the coordination function.

The Inflight Reflex is activated after lift-off. The intention behind the inflight reflex is on the one hand the necessity to ensure a proper landing posture in order to minimize the mechanical stress on the joints and segments and on the other hand to maintain favorable joint angles to maximize the amount of impact energy that can be restored in the subsequent push off attempt. The approach taken here is the

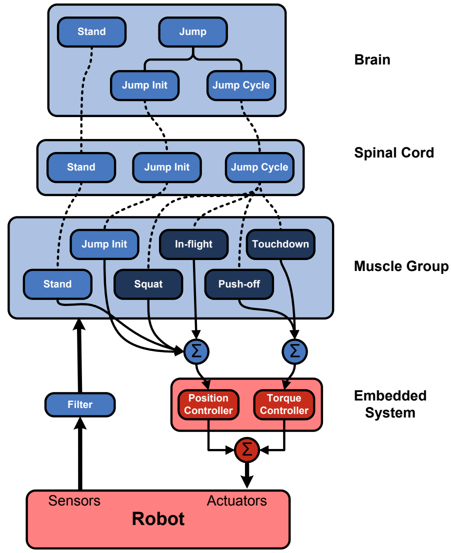


Fig. 4 Schematic view of the behavior based control structure.

combination of both by using two concurrent reflexes: the already mentioned inflight reflex and a touchdown reflex that will be introduced in the next section. The activity of this reflex (and therefore the stiffness of the joint angle controller) decreases the closer the sensed joint configurations approaches the desired one (slightly bend). Once the target configuration is reached within a certain threshold the activity is kept at a level of approx. 30 % to ensure the posture remains roughly the same. The reduction of the activity has proven to be very useful at the moment of touchdown since a desired amount of joint compliance can be realized this way. The stimulation is entirely withdrawn from the reflex as soon as a ground contact is detected and thus the landing can be assumed.

The Touchdown Reflex as mentioned above is pre-stimulated at a certain point in time while the leg is still in the air. Once ground contact is detected the reflex intends to gradually slow down the drop until the leg comes to a complete rest at a defined position. The former is achieved through the touchdown reflex while the latter is managed by the squat reflex to be described in the next section. The activity of this reflex is adjusted in respect to the angular velocity. The higher the angular velocity the more counter momentum (i.e. torque) is applied to the actuated joints.

The Squat Reflex is once stimulated at the beginning of the landing phase. The squat reflex is as already stated responsible for controlling the legs configuration into a defined resting position (hip angle $\approx 30^\circ$, knee angle $\approx 60^\circ$) by means of position control. By co-activating the touchdown reflex one can be sure to reach that position with only rather low velocity and thus tolerable mechanical stress for the hardware.

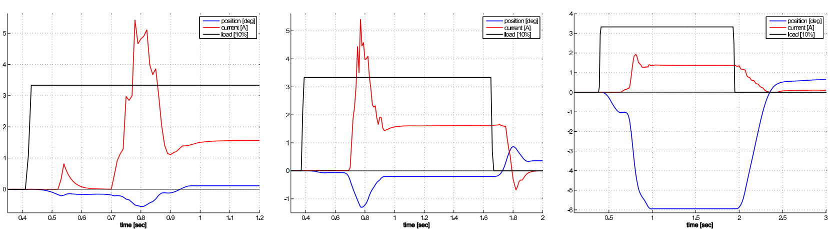
The Touchdown Preflex is intended to reduce the impact stress. The idea is to adjust the speed of the contact point to the ground. This results in adduction of the leg after the peak of the airborne phase is passed. The timing is very critical. If the preflex is activated too early it is no longer active during the impact since the inflight reflex is trying to maintain a safe landing position and thus useless. If it is activated too late it can not unfold its full effect.

5 Experiments and Results

5.1 Compliant Controller

In order to be able to test the implemented controller under the best possible conditions, the second actuator is mounted on the same shaft as the first one. This results in a direct and stiff connection of the two gearboxes. One of the motors is controlled using the hierarchical controller while the other is used to simulate a controlled load by directly applying the PWM ratio. To test the desired compliant properties, the controller was set to a ”soft” position control ($w_{pos} < 1$, $w_{tor} = 0$) and the second motor was used to generate a sudden and heavy distortion. The results can be found in figure 5.

As expected the tolerance to deviation in position increases with decreasing w_{pos}. In figure 5(a) and 5(b) the controller is stiff enough to compensate the position deviation nearly completely. A very small deviation is left in the intermediate case. The compliant controller is not able to hold the desired position. With a higher w_{pos} setting the controller reacts more aggressive (in respect to magnitude and time) to an occurring distortion. With a lower value the behavior is more relaxed and the current overshoot is way smaller. The applied counter momentum in the static case is equal for all parameter setups. The time delay between the load jump and the reaction of the position is caused by the loose connection between the two motors.



(a) stiff (b) intermediate (c) compliant

Fig. 5 Qualitative performance of the real compliant position controller based on the stiffness weight. The dotted line represent the current measured in Ampere, the solid one stand for the current position denoted in degree while the dashed graph indicates the load applied by the second motor in voltage.

5.2 Simulated Jump Cycles

In order to be able to optimize the jumping process without putting the actual hardware in jeopardy a simulation environment consisting of an hardware abstraction layer and the physics simulation engine Newton was employed. The results of an undisturbed jump cycle can be found in figure 6.

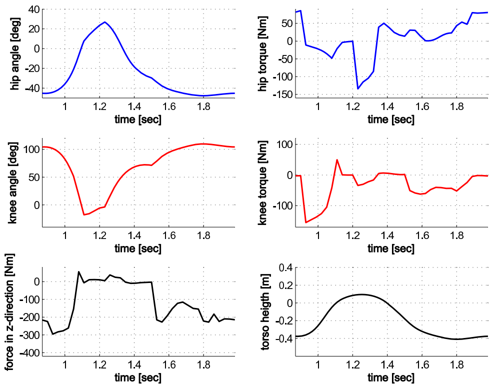


Fig. 6 Sensor data recorded during one jump sequence.

The dashed graphs (top) denote the hip torque and angle, while the dotted ones (middle) stand for the respective knee values. On the bottom the load cell data (left, solid) and the hip-joints z-position (right, dot-dashed) are marked. The cycle starts with the pushoff phase $t = 1.9\ s$ until the liftoff is reached at $t = 2.1\ s$. The impact occurs at $t = 2.5\ s$ as visible in the load cell data. The recording continues until the initial squatted position is reached again after a cycle time of $t = 1.1\ s$. The acquired jump height is approximately 15 cm. The lion's share of the work in the phase prior to liftoff is performed by the knee, because the hip actuator is only able to apply vertical forces to the leg. The ratio shifts after the leg is airborne. In this phase the hip motor has the role to bring the leg in the landing position. Due to the inertia of the tibia, the knee motor can be relaxed to reach the desired knee angle. The preflex helps to reduce the impact force of formally over 350 N to approx. 230 N. We have compared the hip and the knee angle with such of humans. Although it was not our goal to copy the trajectory of humans the behavior is approximately equal.

6 Conclusion and Outlook

In this paper the lower layers of a biologically motivated control architecture for biped robots were derived. The approach features compliant behavior and distributed control. The performance of the reflex-like control was evaluated using simulated cyclical jumps of a single leg with passive elastic elements. The biological motivated actuator controller was implemented and tested within an experimental setup of the prototype leg.

As can be seen in the experimental results, a behavior similar to a SEA could be obtained with a standard DC motor. This is possible by employing a low-friction gearbox and a fast hierarchical compliant controller. However the actively controlled stiffness can be altered by changing a single parameter. This might lead to an entirely stiff joint behavior on the one side or an unrestrained limb movement on the other. The approach has shown its potential during repetitive jumping in a simulated environment.

The next step will be to execute jumping motions with the prototype leg. Furthermore experiments concerning the effectiveness of a passive ankle joint will be pursued. After that the physical distribution of the reflexes will be taken into consideration.

References

1. Albu-Schaeffer, A., Hirzinger, G.: Cartesian impedance control techniques for torque controlled light-weight robots. In: Proceedings of the 2002 IEEE International Conference on Robotics and Automation (ICRA), Washington, DC, USA, vol. 1, pp. 657–663 (2002)
2. Anderson, S., Wisse, M., Atkeson, C., Hodgins, J., Zeglin, G.J., Moyer, B.: Powered bipeds based on passive dynamic principles. In: Proceedings of the 2005 5th IEEE-RAS International Conference on Humanoid Robotics, pp. 110–116 (2005)
3. Bizzi, E., Cheung, V., d'Avella, A., Saltiel, P., Tresch, M.: Combining modules for movement. Brain Research Reviews 57, 125–133 (2007)
4. Bobbert, M.F.: Dependence of human squat jump performance on the series elastic compliance of the triceps surae: A simulation study. The Journal of Experimental Biology (2001)
5. Collins, S., Ruina, A.: A bipedal walking robot with efficient and human-like gait. In: Proceedings of the 2005 IEEE International Conference on Robotics and Automation (ICRA), Barcelona, Spain, pp. 1983–1988 (2005)
6. Curran, S., Orin, D.: Evolution of a jump in an articualted leg with series-elastic actuation. In: IEEE International Conference on Robotics and Automation (ICRA), Pasadena, CA, USA, pp. 352–358 (2008) ISSN 978-1-4244-1647-9
7. Ham, R.V., Damme, M.V., Vanderborght, B., Verrelst, B., Lefeber, D.: Maccepa, the mechanically adjustable compliance and controllable equilibrium position actuator. In: ACTUATOR 2006: The 10th International Conference on New Actuators, Bremen, Germany (2006)
8. Ivanenko, Y.P., Poppele, R.E., Lacquaniti, F.: Five basic muscle activation patterns account for muscle activity during human locomotion. Journal of Physiology 556 (2004)
9. Ivanenko, Y.P., Poppele, R.E., Lacquaniti, F.: Motor control programs and walking. The Neuroscientist 12(4), 339–348 (2006)
10. Kerscher, T., Zöllner, J., Dillmann, R., Stella, G., Caporaletti, G.: Model and control of compliant joints driven by fluidic muscles. In: ACODUASIS-workshop, Torino, Italy (2005)

11. Lemay, M.A., Galagan, J.E., Hogan, N., Bizzi, E.: Modulation and vectorial summation of the spinalized frog's hindlimb end-point force produced by intraspinal electrical stimulation of the cord. IEEE Transactions on Neural Systems and Rehabilitation Engineering 9 (2001)
12. Lohmeier, S., Buschmann, T., Ulbrich, H., Pfeiffer, F.: Humanoid robot lola - research platform for high-speedwalking. In: Motion and Vibration Control, pp. 221–230. Springer, Netherlands (2009)
13. Luksch, T., Berns, K.: Controlling dynamic motions of biped robots with reflexes and motor patterns. In: Fourth International Symposium on Adaptive Motion of Animals and Machines (AMAM), Cleveland, USA, pp. 115–116 (2008)
14. Luksch, T., Berns, K.: Initiating normal walking of a dynamic biped with a biologically motivated control. In: 11th International Conference on Climbing and Walking Robots (CLAWAR), Coimbra, Portugal (2008)
15. Luksch, T., Berns, K., Mombaur, K., Schultz, G.: Using optimization techniques for the design and control of fast bipeds. In: 10th International Conference on Climbing and Walking Robots (CLAWAR), Singapore (2007)
16. McGeer, T.: Dynamics and control of bipedal locomotion. Journal of Theoretical Biology 163, 277–314 (1993)
17. Pfaff, G., Meier, C.H.: Regelung elektrischer Antriebe II, 3rd edn. Oldenbourg Verlag (1992) ISBN 3-486-22376-3
18. Pratt, J., Chew, C., Torres, A., Dilworth, P., Pratt, G.: Virtual model control: An intuitive approach for bipedal locomotion. International Journal of Robotics Research 20(2), 129–143 (2001)
19. Pratt, J., Krupp, B., Morse, C.: Series elastic actuators for high fidelity force control. Industrial Robot Journal 29(3), 234–241 (2002)
20. Proetzsch, M., Luksch, T., Berns, K.: Robotic systems design using the behavior-based control architecture ib2c. Journal of Robotics and Autonomous Systems (submitted, 2008)
21. Rossignol, S., Dubuc, R., Gossard, J.P.: Dynamic sensorimotor interactions in locomotion. Physiological Reviews 86, 89–154 (2006)
22. Zehr, E., Stein, R.: What function do reflexes serve during human locomotion? Progess in Neurobiology 58, 185–205 (1999)