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# Experiments on Embodied Cognition: A Bio-Inspired Approach for Robust Biped Locomotion

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## 1. Introduction

Recently, the psychological point of view that grants the body a more significant role in cognition has also gained attention in artificial intelligence. Proponents of this approach would claim that instead of a 'mind that works on abstract problems' we have to deal with and understand 'a body that needs a mind to make it function' (Wilson, 2002). These ideas differ quite radically from the traditional approach that describes a cognitive process as an abstract information processing task where the real physical connections to the outside world are of only sub-critical importance, sometimes discarded as mere 'informational encapsulated plug-ins' (Fodor, 1983). Thus most theories in cognitive psychology have tried to describe the process of human thinking in terms of propositional knowledge. At the same time, artificial intelligence research has been dominated by methods of abstract symbolic processing, even if researchers often used robotic systems to implement them (Nilsson, 1984).

Ignoring sensor-motor influences on cognitive ability is in sharp contrast to research by William James (James, 1890) and others (see (Prinz, 1987) for a review) that describe theories of cognition based on motor acts, or a theory of cognitive function emerging from seminal research on sensor-motor abilities by Jean Piaget (Wilson, 2002) and the theory of affordances by (Gibson, 1977). In the 1980s the linguist Lakoff and the philosopher Johnson (Lakoff & Johnson, 1980) put forward the idea of abstract concepts based on metaphors for bodily, physical concepts; around the same time, Brooks (Brooks, 1986) made a major impact on artificial intelligence research by his concepts of behavior based robotics and interaction with the environment without internal representation instead of the sense-reason-act cycle. This approach has gained wide attention ever since and there appears to be a growing sense of commitment to the idea that cognitive ability in a system (natural or artificial) has to be studied in the context of its relation to a 'kinematically competent' physical body.

Among the most competent (in a multi functional sense) physical bodies around are certainly humans, so the study of humanoid robots appears to be a promising field for

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understanding the mechanisms and processes involved in generating intelligence in technical systems.
In the following we will give an overview of the field of humanoid robot research.

## 2. State of the Art Humanoids

A review on humanoid robot systems, cannot be made without bearing in mind that many of the current developments concentrate on one or the other feature of human performance. Some of them are good at manipulating objects with anthropomorphic arms but move over a wheeled platform. Some others walk on two legs but lack of a torso and arms. Some combine those two features but lack a human appearance or communication abilities. Some other developments concentrate on human-like communication skills, like speech recognition, gestures and the generation of facial expressions that denote sadness, happiness, fear or any other state that a human is able to recognise. All these aspects are crucial for the final goal of attaining a robot that is perceived as humanoid. A robot that transmits its feelings, ideas or thoughts, that behaves like a human when performing a task or a movement and with which a human feels safe and confident to collaborate with are key points for the social acceptance of a humanoid robots.
A description of the state of the art might start chronologically since the development of the first complete humanoid, the Wabot-1 from the Waseda University in 1970 but we choose to list the developments on the humanoid field beginning with the systems that incorporate the more human-like features and are considered the most advanced systems to continue describing systems that work on single or a combination of several human-like aspects, all of them of major interest and importance.
Before describing the most important developments on the field, it is worth mentioning a few aspects about observable facts depending on the origin of the robot: namely, Asia, Europe or USA. There are differences on the complexity of the systems but also on the different approaches that are followed or the motivations that lead the development of the robot. Japan (and Korea in a minor extent) are seen as world leaders in the humanoid robot research. They have the most complex robots with the most similar human resemblance. They believe in a complete immersion of the robots in a future society, where robots do not differentiate easily from humans. The more remarkable points of their developments are the hardware (the mechanics), the physical appearance of the robot and the fact that the industry is leading the research on these robots, expecting a huge market in a near future. USA entered the humanoid era because of the needs posed by the claims of the 'modern' Artificial Intelligence: the need for a human-like body as a prerequisite for a robot to achieve human-like intelligence. It is the interaction with the environment and the gathered experience what is thought to be the basis for the appearance of intelligent behaviors. Europe, on the other side, is basically concerned with giving a real application to the development of humanoid robots and that is on the service robotics area, for rehabilitation and/or personal care of the elderly. The most advanced systems are heading towards that goal. At the same time, inspiration from biological systems is a very common term to describe the approaches used in those robots. Several European projects work on sensorimotor coordination, cognitive architectures and learning approaches that have their roots in the cooperation with scientists in the neuroscience, biology and psychology areas.
The ASIMO robot from Honda (Hirai, 1998) (cf. figure 1) is without a doubt the most advanced humanoid robot nowadays. Honda employed vast human and economical

resources to achieve a complete human-like looking robot, pushing forward the research in many areas. The current research model is 130cm tall, weights 54 kg and is able to run at 6km/h (December 2005). The research began in 1986, achieving a first ASIMO prototype in the year 2000. Nowadays, ASIMO is the only robot that is able to autonomously walk around and climb stairs and slopes. Furthermore, it is able to understand some human gestures and interact with people using its speech recognition system and some pre-programmed messages. ASIMO can also push a cart, keeping a fixed distance to it while moving and still maintaining the capability to change direction or speed of movement, walking hand-in-hand with a person or carrying a tray.

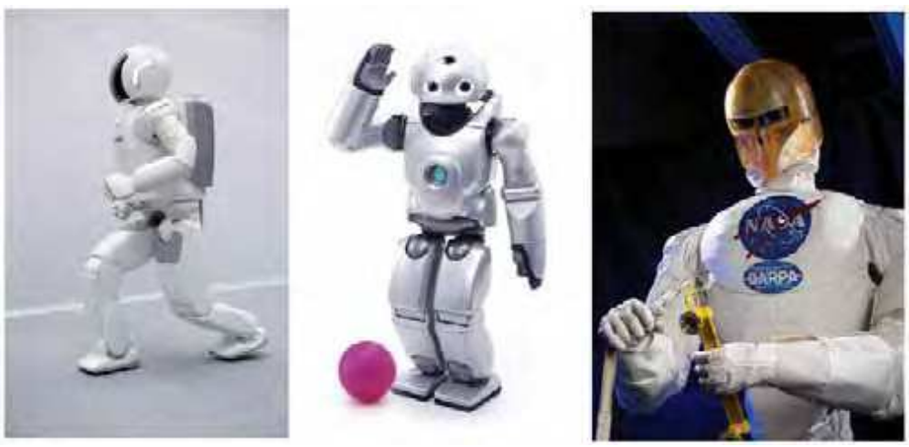


Fig. 1. Honda ASIMO (left picture), Sony QRIO (middle picture), and ROBONAUT (right picture).

The HRP-2P (Kaneko, 2003) robot specified by AIST (National Institute of Advanced Industrial Science and Technology, Japan) and whose hardware was manufactured by the Kawada Industries (a company that also worked with Honda and the University of Tokyo in the development of the ASIMO and the H6-H7 robots) is one of the most advanced humanoids nowadays. It differs from ASIMO on the fact that it is a research prototype whose software is open to any roboticist. Moreover, it was designed to walk on uneven terrains and recover from falling positions, features not yet possible for ASIMO. It weights 58kg and is 154cm tall.

Probably the third robot in importance in Japan is the H7 (Kagami, 2001) from the University of Tokyo. However, there is not much information available apart from videos showing its capabilities walking on a flat terrain. As above mentioned, Kawada Inc. was responsible for the hardware development. It weights 55kg, is 147cm tall and has 30 DoF.

Sony entered the humanoid world in 1997 with the SDR-1X series, achieving the SDR-4X version in 2003, named QRIO (Ischida, 2003) (cf. Fig. 1) as was intended to be commercially available. In 2006 Sony announced the decision to stop the further development of the robot. QRIO is comparable to ASIMO in its walking capabilities although since it was designed as an entertainment robot, its size is substantially smaller than ASIMO: its weights 7kg and is 58cm tall. Its main features include the ability to adapt its walking to the most difficult situations: from walking on irregular or tiled terrains to react to shocks and possible falling

conditions. But since its origins as entertainment robot, the most remarkable features are those that enhanced its interaction capabilities with people: the robot is able to recognise faces, use memory to remember a previously seen person or his/her words, detect the person who is speaking and incorporates a vocabulary of more than 20,000 words that enables the robot to maintain simple dialogues with humans.

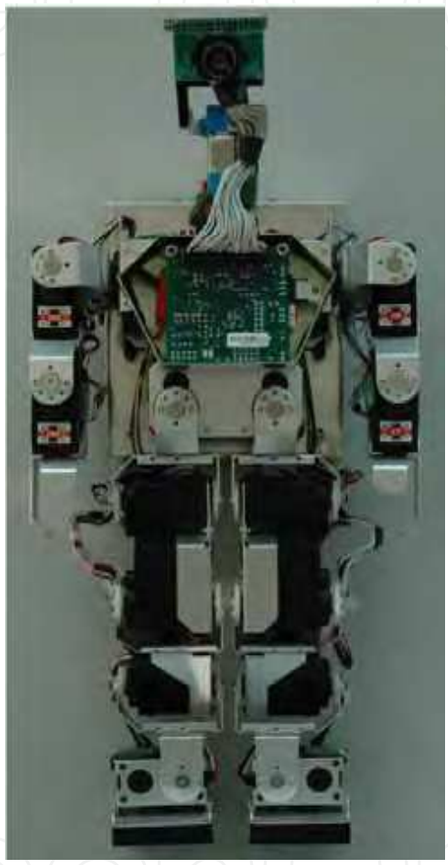

Fig. 2. The Robot BIN-HUR based on Kondo's KHR-1.

Hubo (Il Woo, 2005) is the most well-known humanoid robot in South Korea and one of the world's most advanced. It is the latest development of the series of KHR robots (KHR-1, KHR-2 and KHR-3 – Hubo). It is 125cm tall and weights 56kg, having 41 DoF. Apart from improving in this latest version its walking abilities, Hubo is now also able to talk to someone by using a speech recognition system.

Fujitsu also entered the humanoid area in 2003 with the HOAP-1 (Murase, 2001). Its major claim with it was its learning capabilities and the use of neural networks to control the locomotion implementing a Central Pattern Generator (CPG), proven to be one of the responsible neural circuitry for the locomotion on vertebrates. These artificial neural

oscillators are used to create rhythmic motions to generate the appropriate gait. The major advantage is claimed to be its adaptation to the environment and new terrain configurations and the minimum computational effort to control the locomotion. No need for modelling kinematics, dynamics or generating stable trajectories using complex criteria are required. It was intended to be used in research labs and universities as an educational tool where to test different algorithms and for that reason provides an open source software and weights only 6kg and is 48cm tall. It can walk up to 2km/h and is sold at about 50,000€. In 2004, HOAP-2 received the Technical Innovation Award from the Robotics Society of Japan.

Toyota also presented a series of partner robots (2005), one of them walking in two legs, finding its application in the elderly care and rehabilitation. As a curious feature, Toyota included artificial lips with human finesse what, together with their hands, enables them to play trumpets in a similar way a human does.

WABIAN-RIII and WENDY (Ogura, 2004) are the latest developments from the Waseda University, as already mentioned, the pioneers in the humanoid field with the first full-scale humanoid robot, a project that began in 1970 and finished three years later with Wabot-1. WABIAN-RII continues the research in dynamical walking plus load carrying and the addition of emotional gesture while performing tasks. Likewise, WENDY incorporates emotional gestures to the manipulation task that is being carried out. WABIAN-RII weights 130kg and is 188cm tall while WENDY is 150cm tall and weights 170kg.

Johnnie (Löffler, 2000) is probably the most well-known and advanced humanoid robot in Europe. It was developed at the University of Munich with the aim of realising a human-like walking, in this case based on the well-established Zero Moment Point (ZMP) approach introduced by Honda in the ASIMO robot, but with the aid of a vision system. It is able to walk on different terrains and climb over some stairs. It is 180cm tall and weights 45kg.

Robonaut (Ambrose, 2001) (cf. figure 1) is a humanoid robot developed by the NASA with the aim of replacing a human astronaut in EVA tasks (outside the vehicle). The main feature of the robot is a human dexterous manipulation capability that enables it to perform the same tasks an astronaut would perform and with the same dexterity. The robot is not autonomous but tele-operated from inside the vehicle. Since legs have no utility in space, the robot is composed of two arms and a torso that is attached to a mechanical link enabling the positioning of the robot in any required position/orientation. Because of the bulky suits the astronauts have to wear to protect against radiations, their manipulation capabilities are greatly reduced and the handles, tools and interfaces they use are designed to be handled with their special gloves. A robot, even though needing some protection against radiation, would not required such a bulky suit thus recovering to a certain extent a human dexterity. Moreover, risks for astronauts are avoided on these missions outside the spatial vehicle. It has the size of a human torso and arm, with 54 DoF in total: 14 for each hand, 7 for each arm and the link to the vehicle, 2 in the neck and 3 on the waist.

In the field of human-robot interaction, the robot Cog (Brooks, 1998), from the MIT AI Lab, is the best example. Cog is composed of a torso, two arms and a head. The main focus of this project is to create a platform in order to prove the ideas exposed by Rodney Brooks claiming that human-like intelligence appearance requires a human-like body that interacts with the world in the same way a human does. Besides, for a robot to gain experience in interacting with people it needs to interact with them in the same way people do. One underlying hope in Brooks theory is that: Having a human-like

shape, humans will more easily perceive the robot as one of them and will interact with it in the same way as with other people, providing the robot with valuable information for its interaction learning process. These ideas have been taken to the next level with Kismet (Breazeal, 1998), which is also a robot from the same Lab. In this case, a robot composed of a human-like head. The research focus is on natural communication with humans using, among others, facial expressions, body postures, gestures, gaze directions and voice. The robot interacts in an expressive face-to-face way with another person, showing its emotional state and learning from humans as kind of a parent-child relation.

In the same direction, the Intelligent Robotics Lab of the University of Osaka (Japan) developed in 2005 the most human-looking robot so far. It is a female robot named Repliee Q1Expo (Ishiguru, 2005). Its skin is made of silicon what gives it a more natural appearance and integrates a vast number of sensors and actuators to be able to interact with people in a very natural and friendly way. Even the chest is moved rhythmically to create the illusion that the robot is breathing.

However, as promising as some of these developments seem to be at first glance, one has to carefully evaluate what exactly can be learned for the field of 'embodied cognition' from the study of more or less isolated features of human behavior, whether that be in the field of complex locomotion, manipulation or interaction. In her paper (Wilson, 2002) identifies six viewpoints for the new so-called 'embodied cognition' approach:

1) Cognition is situated: All Cognitive activity takes part in the context of a real world environment.
2) Cognition is time pressured: How does cognition work under the pressures of real time interaction with the environment
3) Off-loading of cognitive work to the environment: Limits of our information processing capabilities demand for off-loading.
4) The environment is part of the cognitive system: because of dense and continuous information flow between the mind and the environment it is not meaningful to study just the mind.
5) Cognition is for action: Cognitive mechanisms (perception/memory, etc.) must be understood in their ultimate contribution to situation-appropriate behavior.
6) Off-line Cognition is body-based: Even when uncoupled from the environment, the activity of the mind is grounded in mechanisms that evolved for interaction with the environment.

We have cited all six viewpoints here, as they represent an interesting perspective on the state of the art in embodied cognition. In the experimental work presented here we focus our attention on viewpoint 2 that appears to have a crucial instantiation especially in humanoid robots that have to find a way to effectively and efficiently counteract the effects of gravity while walking. In fact looking at viewpoint 3 and 4 counteracting appears to be wrong from the beginning instead having gravity work for the system appears to be a better way of achieving robust locomotion in a technical two legged system.

## 3. Robust Biped Locomotion Control

In this section we describe an experiment with a humanoid robot that achieves robust locomotion in the absence of a kinematical model. For stable goal directed behavior it relies

solely on two simple biological mechanisms that are integrated in an architecture for low level locomotion control.

### 3.1. The Hardware

The robot (see figure 2) is based on the Kondo KHR-1 construction kit and has 18 DOFs, 5 per leg, 3 per arm, and 2 as pan tilt unit for the head. The system is 40 cm high (30 cm shoulder-height) and has a total weight of 1.5 Kg. Its mechanics are mainly part of the Kondo KHR-1 construction kit. As control unit we use a custom-made microcontroller board.

An ADXL202 tilt sensor was integrated in the upper body to provide information about the pitch of the robot. Pressure sensors in the feet indicate if they have ground contact. For wireless communication we use a Bluetooth module. The head consist of a CMUCam2 which is used for color tracking affixed on a pan tilt unit.

The microcontroller board is composed of an MPC 565 PowerPC microcontroller mounted on a custom-designed mainboard. The MPC 565 is running at 40 MHz, has 2 MB flash memory and 8 MB RAM. Amongst others it is equipped with three time processing units (TPUs) each with 16 channels, two analog digital converter modules (ADCs) each with 64 channels, and two RS-232 interfaces.

The mainboard provides 32 Servo plug-in positions which are connected to two of the TPUs to generate pulse width modulated (PWM) signals for the activation of the Servos. Furthermore, the plug-in positions are connected to the ADCs to feed back the servo's current and the actual position on the basis of its potentiometer value.

Two more plug-in positions each with 8 pins are linked with the ADCs to connect additional analog sensors, e.g. tilt sensors or pressure sensors.

The CMUCam2 is an intelligent camera module which was developed at the Carnegie Mellon University. It has the integrated possibility to track colors and to communicate over a RS-232 connection. In our case we will use it to track the color of a ball, which will be provided as sensory information for a higher level behavior whose intention it is to follow the ball

### 3.2 The control architecture

Our architecture is based on two approaches to robust and flexible real world locomotion in biological systems, which seem to be contradictory at first sight. These are the Central Pattern Generator (CPG) model and the pure reflex driven approach.

A CPG is able to produce a rhythmic motor pattern even in the complete absence of sensory feedback. The general model of a CPG has been identified in nearly every species even though the concrete instantiations vary among the species to reflect the individual kinematical characteristics in the animals.

The idea therefore seems to be very promising as a concept to realize locomotion in kinematically complex robotic systems, see figure 3. As it resembles the divide and conquer strategies that are reflected in nearly all solutions to complex control problems.

Another model for the support of robust locomotion is also provided by evolution in the animal kingdom. This is the concept of reflex based control (Delcomyn, 1980). A reflex can be viewed as a closed loop control system with fixed input/output characteristics. In some animals, like the locust, this concept is said to actually perform all of the locomotion control and no further levels of control, like the CPG, are involved (Cruse, 1978).

Whether or not complex motion control can be achieved only via reflex systems is subject to further discussion, however, the concept of a set of fixed wired reactions to sensory stimuli is of high interest to roboticists who aim to gain stability in the systems locomotion.

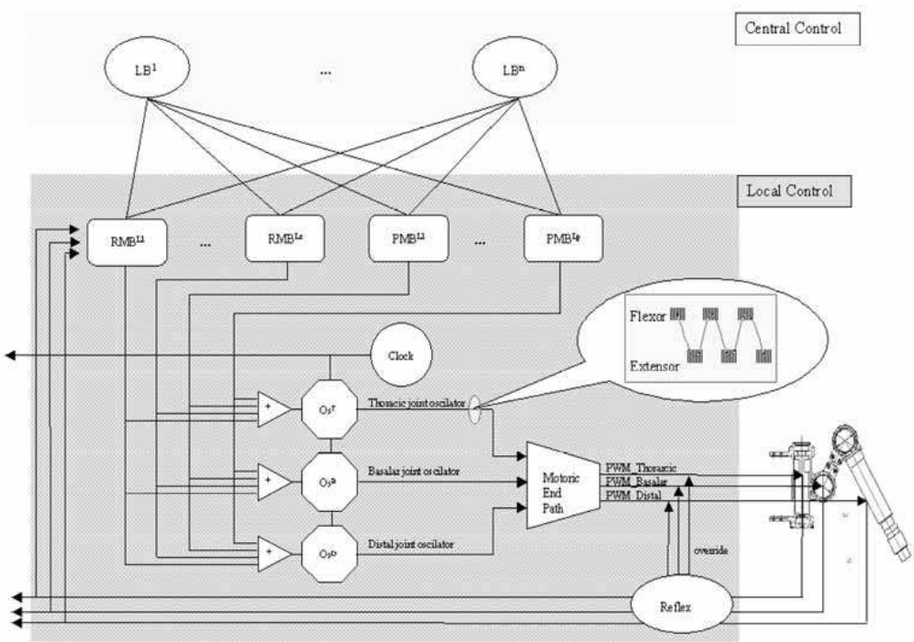


Fig. 3. The low level control architecture. On the global level (light gray area) we have implemented Locomotion Behaviors (LB's), typically (Forward, Backward and Lateral locomotion). These global behaviors are connected to all local leg controllers and activate the local single leg motion behaviors. The local level (dark gray area) implements Rhytmic Motion Behaviors (RMB's) and Postural Motion Behaviors (PMB's). These behaviors simultaneously influence the amplitude and frequency parameters of –in this case- three oscillating networks (OST, OSB and OSD). The oscillators are connected to a common clock which is used for local and global synchronization purposes. The oscillators output is a rhythmic, alternating flexor and extensor, stimulation signal (see callout box), which is translated into PWM signals via the motoric end path. Inline with the output of the motoric end path are a set of pertubartion specific reflexes, which override the signals on the end path with precompiled activation signals if the sensor information from the physical joints meets a set of defined criteria.

The design of the control architecture described here was thus driven by these two concepts. The CPG approach appeared to be interesting to generate rhythmic walking patterns which can be implemented computationally efficient, while the reflex driven approach seemed to provide a simple way to stabilize these walking patterns by providing: 1) a set of fixed

situation-reactions rules to external disturbances and 2) as a way to bias leg coordination among multiple independent legs (Cruse, 1978). Figure 3 outlines the general idea.
This approach features the idea of continuous rhythmic locomotion as well as postural activity which is generated by spinal central pattern generators in vertebrate systems (Kirchner, 2002), (Spenneberg, 2005).
For our technical implementation, these activities are solely defined by 3 parameters: amplitude, frequency, and offset of the rhythmic movement. Please note the possibility to set amplitude and frequency to zero, just modifying the offset parameter, which would result in linear, directly controlled joint movements. In those cases where amplitude and frequency have non-zero values, the activation patterns will result in a rhythmic movement of the joint around the offset (or baseline) with given frequency and amplitude. To produce complex locomotion patterns, like forward, left, right, or backward movements, all joints of the robot have to be activated simultaneously, while some (legs, shoulder, and hip) actually produce rhythmic activities, others, (like neck, elbow, etc.) will have their amplitude and frequency values set to zero maintaining a position at the offset value. One important aspect of central pattern generators is their nature as feedback control loops, here the so-called proprioceptive information is fed back into the controller and modifies its activity.

## 4. Implementation Issues

Our implementation of the low-level control architecture, shown in figure 5, consists of a combination of drivers and behaviors, which are connected thru special functions (merge functions). Our concept for locomotion is a combination of balance control, see figure 4 and posture behaviors, which should keep the robot balanced while walking or during external interferences. Central Pattern Generator (CPG) behaviors are used to produce rhythmic motions for walking. The speed at which the rhythmic motions are performed is defined by a global clock.

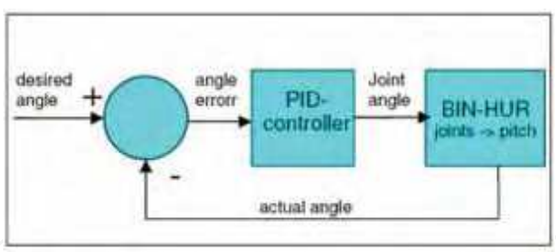


Fig. 4. The control cycle for balance control.

A higher level behavior 'walking' has the task to implement directional walking and another high level behavior 'ball-following' will use the sensory information of the CMUCam2 to follow the intention to track a ball by giving instructions to the walking behavior.

## 5. Experimental Results

To demonstrate a possible result for the activation pattern of a joint while overlaying different CPGs and modifying the posture, we first let the robot walk hanging in the air

without any balancing behavior in order to get even curves. We could not let the robot walk on the ground without balance behaviors because then the system braces and topples down.

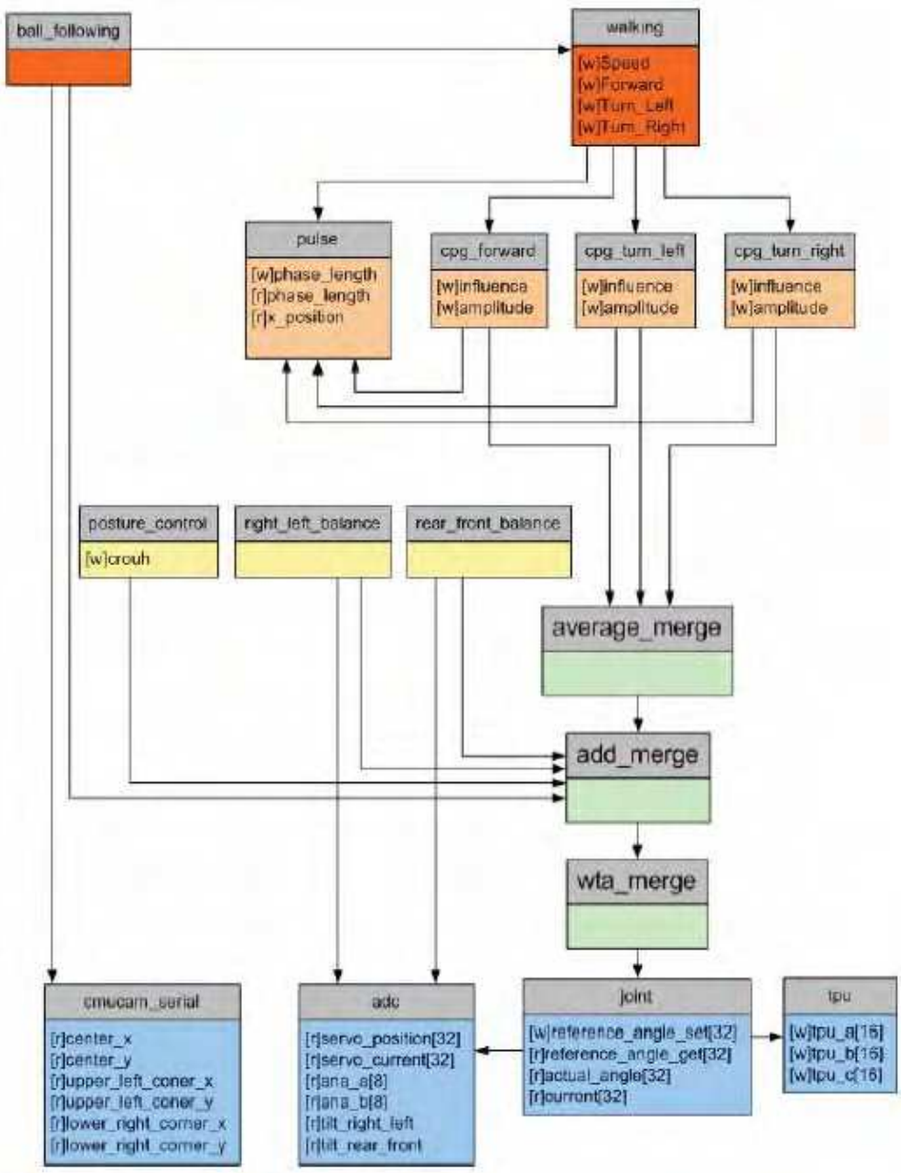


Fig. 5. Implementation of the low-level control concept on the humanoid robot.

Figure 6 shows the desired angles for both hip forward joints at a pulse of 2000 milliseconds. The right and left legs curve are shifted by half the period because one leg is in the swing phase while the other one is in the stance phase.
The rhythm from 0 ms to 15000 ms is only generated by the forward CPG, however, the offset value is set to 10 degrees from 5000 ms to 10000 ms and combined via add merge, thus resulting in a more ducked posture while walking.
From 15000 ms to 21000 ms the forward and turn left CPGs are active and mixed together with an average merge which has the effect that the robot takes a moderate left curve.
In the time segment from 21000 ms to 27000 ms just the CPG for turning left is active and after that there is only a basic posture value.

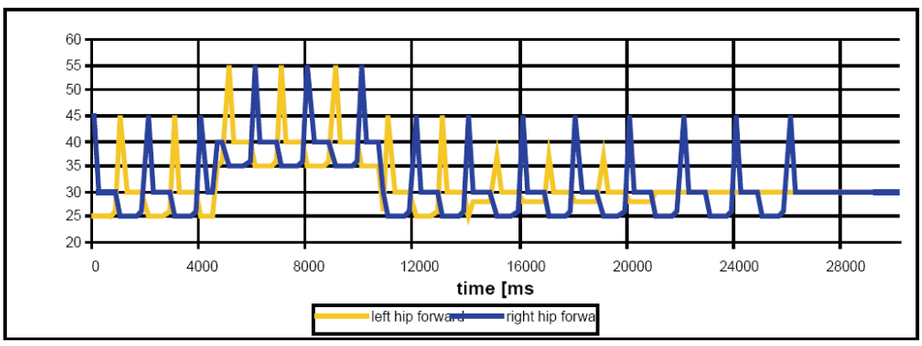


Fig. 6. Reference angle for right and left hip forward joint while walking hanging in the air without balance behaviors.

### 5.1. Walking with balance

When the robot walks on the ground with active balance behaviors, the desired joint angles of the balance behaviors are added to the values of the posture behavior and the active CPGs. In this experiment, we let the robot also walk with a pulse of 2000 milliseconds.
First we let it walk on the ground without active balance behavior to show the desired and real angles of the leg joints with resistance of the gravity and the robot's weight. During this run, shown in figure 9, we prevented the robot from toppling down by hand. From 0 ms to 6000 ms the robot walked forward, and then took a moderate left curve till 12000 ms, and after that it turns left on the spot.
In the second trial, shown in figure 10, we activated the balance behavior. The robot walked forward from 0 ms to 4000 ms, followed by a moderate left curve till 12000 ms, and then turned left on the spot.
As you can see in figure 10, the activation of the balance behavior results in noisier curves than just walking forward without balance behaviors like in figure 9 but it stabilizes the system and prevents it from bracing.
The balance behavior which is designed as a PID-Controller takes the tilt value shown in figure 7 as input for the controller and writes the controller's output values multiplied with a specific factor for each joint to the servos. Negative sensor values represent a right or rather rear leaning, and positive values a left and accordingly front leaning.

As you can see, the output of the PID-Controller shown in figure 8 is less noisy than the tilt sensor values and seems to be more rhythmic. The pattern is repeated every 2000 milliseconds which shows that frequency of the interferences and the retaliatory action depend on the pulse.

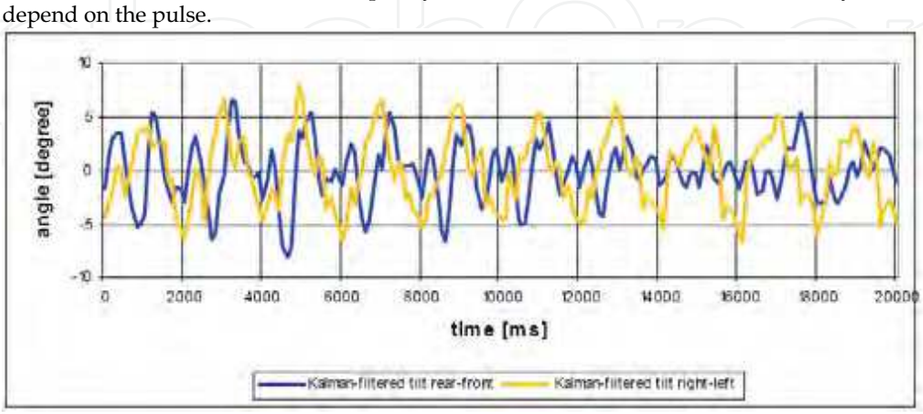


Fig. 7. Values for rear-front and right-left tilt, while walking on the ground with active balance behavior.

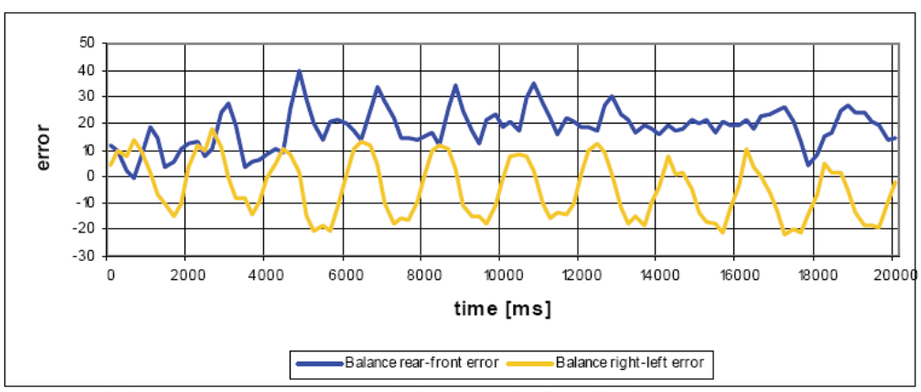


Fig. 8. Calculated error from the balance behavior's PID-Controller while walking on the ground with active balance behavior.

### 5.2. Reaction on a lateral hit

To test the static stability we used the following experimental setup. A ball with a weight of 250 grams was fixed as a pendulum over the robot. The band it is attached with has a length of 15 cm. Then we let the ball fall from a height of 15 cm 5 times and hit the robot at the right shoulder. If we do not activate the balance behaviors the robot cannot absorb the hit just by his stable standing resulting from the posture behavior and topples down. With active balance behaviors the robot tries to react against the hit because of the difference between the desired and the actual leaning and is able to stay and adjust his balance.

Figure 12 shows the desired and real angle of the left arm and leg joints resulting from the reaction of the balance behavior as an average of the 5 recurrences.
Figure 13 shows the perception of the hit by the tilt sensor whose values are used as input for the balance behavior's PID-Controller, shown in figure 14.

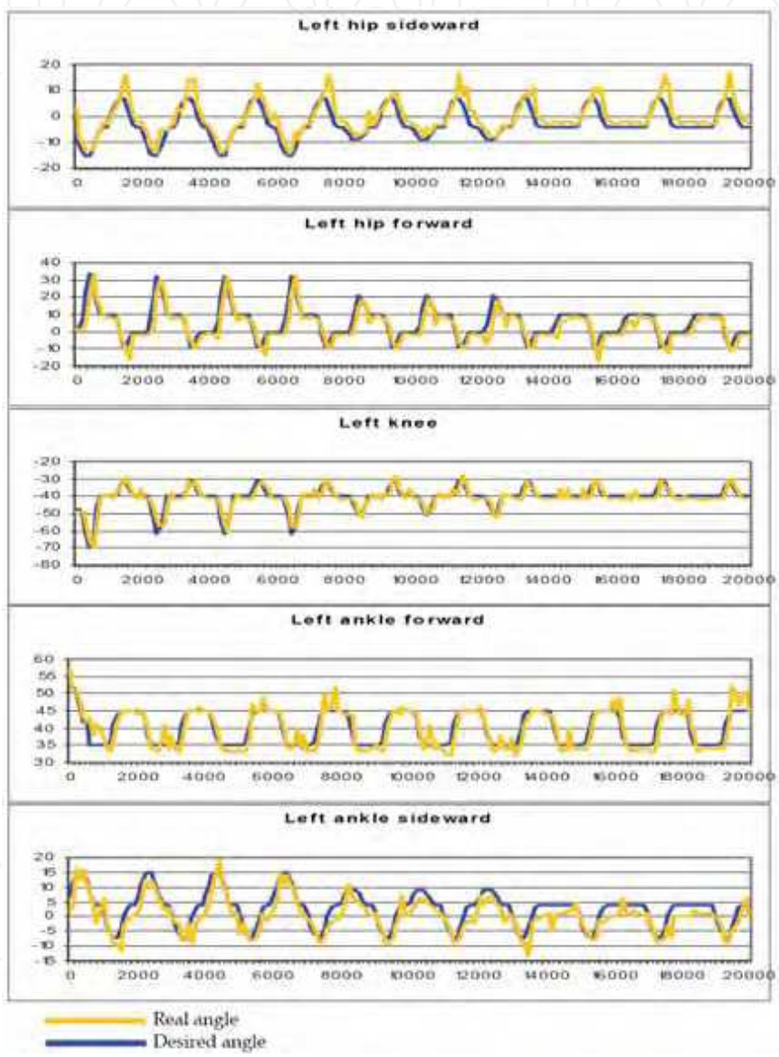


Fig. 9. Desired and real angle (degree) from left leg joints while walking on the ground without active balance behavior over 20000 ms. The robot was prevented from toppling down by hand.

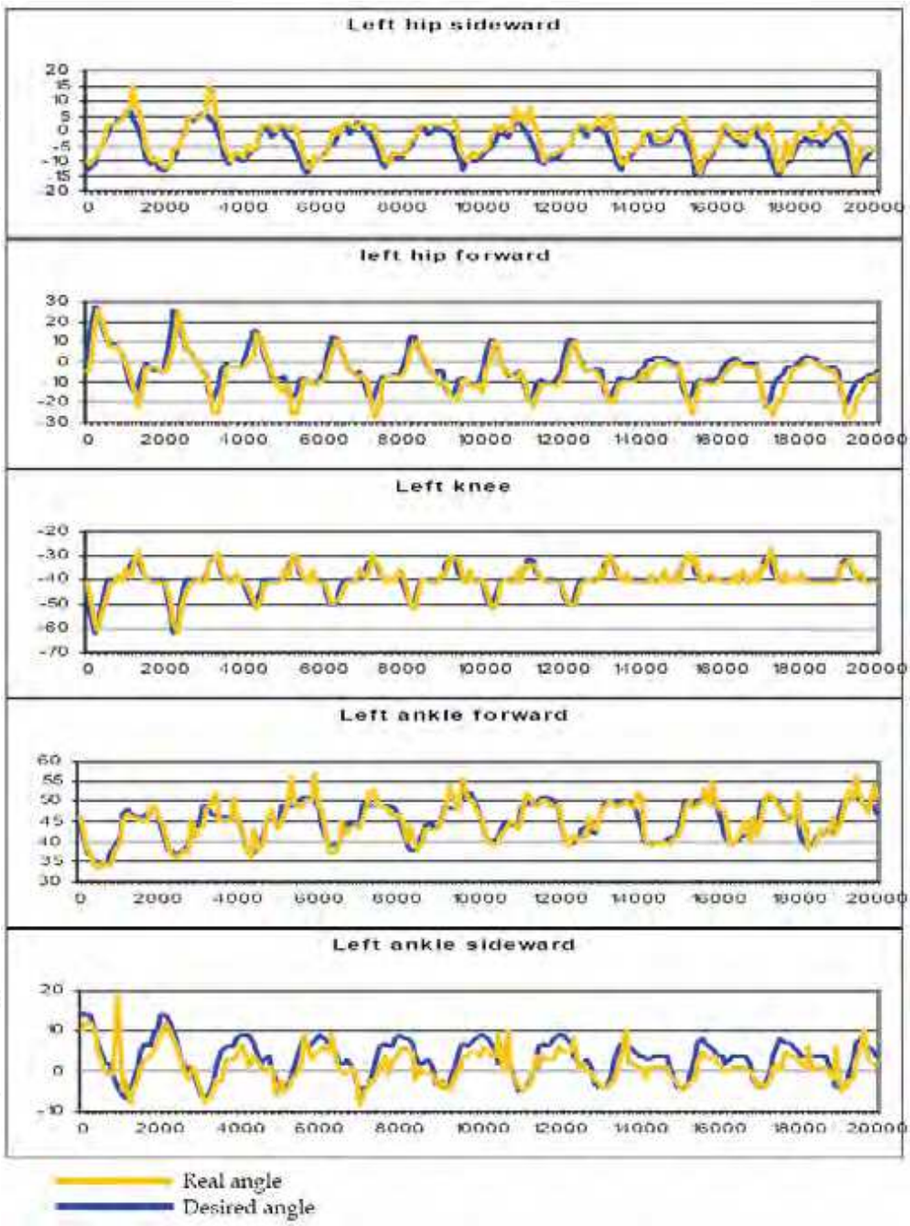


Fig. 10. Desired and real angle (degree) from left leg joints while walking on the ground with active balance behavior over 20000 ms.

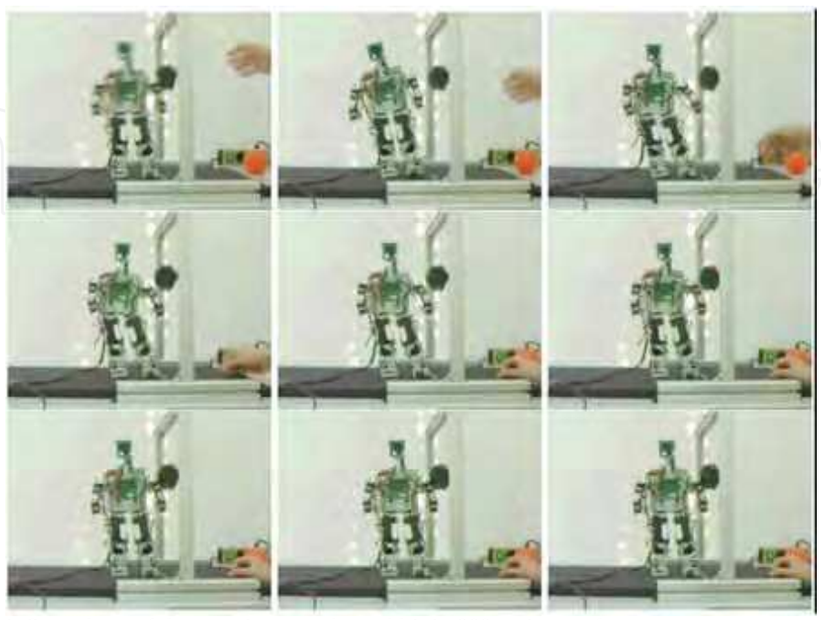

Fig. 11. Snapshots of the reaction on a lateral hit in 200ms intervals.

## 6. Discussions and future work

The CPG based approach for combining rhythmic movements in two-legged robotic systems does work and produces less calculating costs than inverse kinematics (Tevatia, 2000), it results in smoother movements than using simple look up tables, and is easier to realize than neural networks (Shan, 2002). However, direct, goal directed movements are difficult to implement and still require kinematic models of the system.

Recently, we are working on a biologically inspired hybrid learning architecture, see figure 15 for embodied cognition supporting recognition and representation on the basis of sensorimotor coordination. The notion of hybrid architectures is straightforward in the literature, born from the understanding that neither reactive nor deliberative systems provide a sufficient basis for truly cognitive agents. It is therefore natural to postulate systems that contain both types of systems. An important question in these architectures is where to draw the line between the reactive and the deliberative component, and what their relationship should be. Regarding this important question, the architecture we are working on meaningfully combines a reactive layer and a higher level deliberative layer. The reactive layer will be responsible for attention control, object categorization, and reflex triggering.

The locomotion approach we have developed for the humanoid robot will be integrated in the reactive layer and will be exploited in approaching and manipulating objects. The deliberative layer will provide a means for the robot to learn and adapt to new environments. The ball following behavior that we want to implement, for example, can be implemented in the deliberative layer, where behaviors running in the reactive layer can be modulated and combined to achieve the required behavior

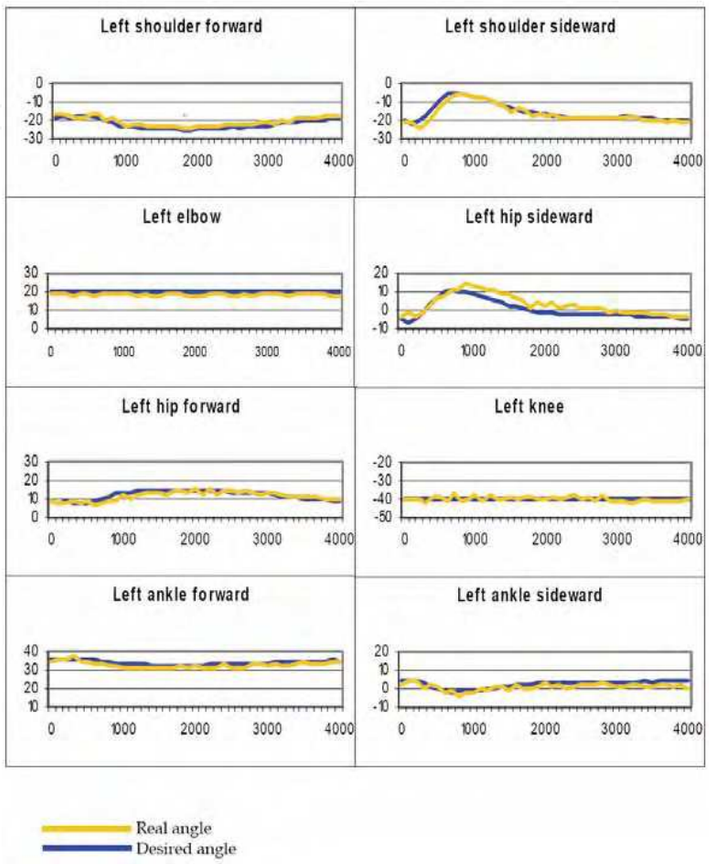


Fig. 12. Desired and real angle (degree) from left arm and leg joints over 4000 ms as an average over 5 recurrences.

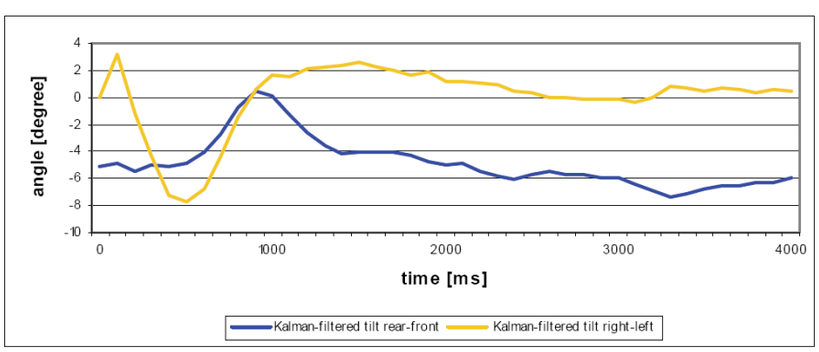


Fig. 13 Tilt values for rear-front and right-left pitch as an average over 5 recurrences.

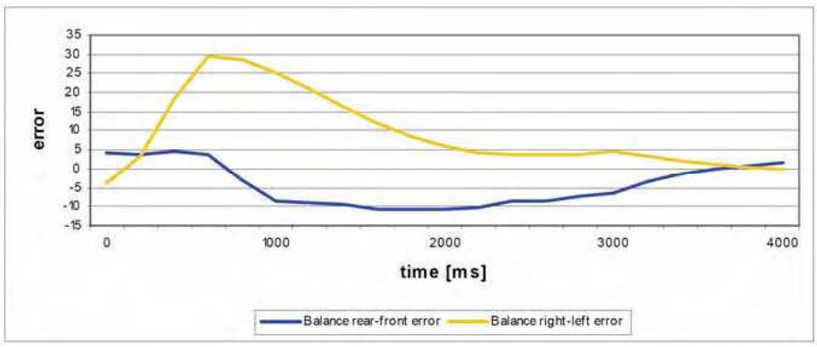


Fig. 14. Calculated error from the balance behavior's PID-controller as an average over 5 recurrences.

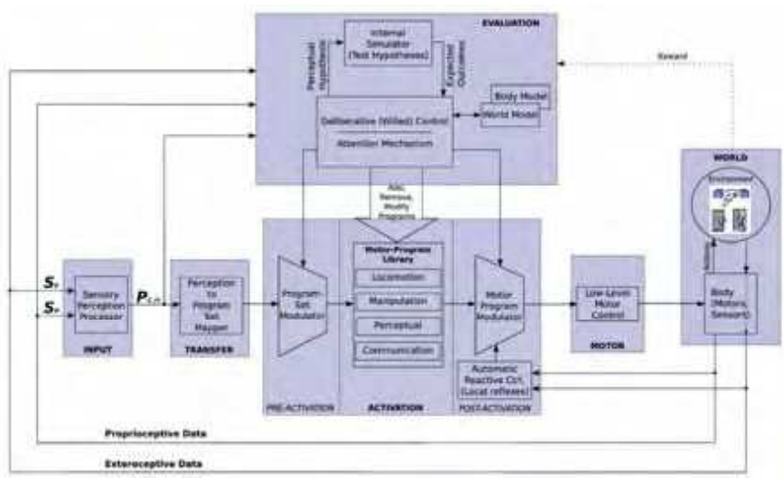


Fig. 15. An architecture integrating learning, representation and robust low-level control.

## 8. References

Albrecht, M., Backhaus, T., Planthaber, S., Stoeppeler, H., Spenneberg, D., & Kirchner, F. (2005). AIMEE: A Four Legged Robot for RoboCup Rescue. In: Proceedings of CLAWAR 2005. Springer.

Ambrose, Robert et al "The development of the Robonaut System for Space Operations", ICAR 2001, Invited Session on Space Robotics, Budapest, August 20, 2001.

Breazeal, C. and Velasquez, J. "Toward Teaching a Robot 'Infant' using Emotive Communication Acts" In Proceedings of 1998 Simulation of Adaptive Behavior, workshop on Socially Situated Intelligence, Zurich Switzerland. 25-40.

Brooks, R. et al "The Cog Project: Building a Humanoid Robot" In Computation for Metaphors, Analogy and Agents, Vol. 1562 of Springer Lecture Notes in Artificial Intelligence, Springer-Verlag, 1998.

Brooks, R. A. (1986). A robust layered control system for a mobile robot. IEEE Journal of Robotics and Automation, 2

Fodor, J.A. (1983). The modularity of mind, Cambridge, MIT Press

Hirai, K. et al "The development of Honda Humanoid Robot" In Proc. of the 1998 IEEE Int. Conf. on Robotics & Automation, p.1321-1326 (1998).

Ishida, T. "A small biped entertainment robot SDR-4X II" In Proceedings of the 2003 IEEE Internation Symposium on Computational Intelligence in Robotics and Automation, pp. 1046-1051, vol.3, 2003

II-Woo Park "Mechanical Design of Humanoid Robot platfrom KHR-3(KAIST Humanoid Robot-3: HUBO)", in Humanoids 2005, Japan

Ishiguro, H. and T. Minato, "Development of androids for studying on human-robot interaction" In Proceedings of 36th International Symposium on Robotics, TH3H1, Dec. 2005.

James, W. (1890). The Principles of Psychology. Henry Holt, New York.

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, & A. Rudolph (Eds.), Neurotechnology for Biomimetic Robots. MIT-Press, MA, USA.

Kaneko, K. et al"Humanoid Robot HRP-2" In Proceedings of the 2004 IEEE International Conference on Robotics& Automation, 2004

Kagami, S. et al"Design and Implementation of Software Research Platform for Humanoid Robotics: H6" In Proc. of International Conference on Robotics and Automation (ICRA'01), pp. 2431--2436 , 2001

Lakoff, G., & Johnson, M. (1980). Metaphors we Live by, University of Chicago Press.

Löffler, K. Gienger, M. "Control of a Biped Jogging Robot" In Proceedings of the 6th International Workshop on Advanced Motion Control, Nagoya, Japan, 307-323, 2000.

Murase, Y. et al "Design of a Compact Humanoid Robot as a Platform" In 19th Conf. of Robotics Society of Japan, p.789-790 (2001)

Nilsson, N.J. (1984). Shakey the robot, SRI Technical Note, no. 323, SRI, Menlo Park, CA, USA.

Ogura, Y. et al"Development of a Human-like Walking Robot Having Two 7-DOF Legs and a 2-DOF Waist" In Proceedings of the 2004 IEEE International Conference on Robotics and Automation, pp134-139, 2004

Prinz, W. (1987). Ideo-motor action. In Heuer, H., & Sanders, A.F. (Eds.) Perspectives on perception and action, p. 47-76, Lawrence Erlbaum Associates, Hillsdale.

Shan, J. Fumio Nagashima (2002). Neural Locomotion Controller Design and Implementation for Humanoid Robot HOAP-1. In: Proceedings of The 20th Annual Conference of the Robotics Society of Japan 2002.

Spenneberg, D. (2005). A Hybrid Locomotion Control Approach. In: Proceedings of the CLAWAR 2005 Conference.

Spenneberg, D., Albrecht, M., & Backhaus, T. (2005). M.O.N.S.T.E.R.: A new Behavior Based Microkernel for Mobile Robots. In: Proceedings of the ECMR 2005.

Spenneberg, D., Hilljegerdes, J., Strack, A., Zschenker, H., Albrecht, M., Backhaus, T., & Kirchner, F. (2005). ARAMIES: A Four-Legged Climbing and Walking Robot. In: Proceedings of 8th International Symposium iSAIRAS.

Tevatia, G. Schaal, S (2000). Inverse kinematics for humanoid robots. In: Proceedings of IEEE International Conference on Robotics and Automation (ICRA 2000)

Toyota Partner Robot. http://www.toyota.co.jp/en/special/robot.

Wilson, M. (2002). Six views of embodied cognition, University of California, Santa Cruz, In Psychonomic Bulletin & Review, 9, p. 625-636.

**Humanoid Robots: New Developments**

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For many years, the human being has been trying, in all ways, to recreate the complex mechanisms that form the human body. Such task is extremely complicated and the results are not totally satisfactory. However, with increasing technological advances based on theoretical and experimental researches, man gets, in a way, to copy or to imitate some systems of the human body. These researches not only intended to create humanoid robots, great part of them constituting autonomous systems, but also, in some way, to offer a higher knowledge of the systems that form the human body, objectifying possible applications in the technology of rehabilitation of human beings, gathering in a whole studies related not only to Robotics, but also to Biomechanics, Biomimmetics, Cybernetics, among other areas. This book presents a series of researches inspired by this ideal, carried through by various researchers worldwide, looking for to analyze and to discuss diverse subjects related to humanoid robots. The presented contributions explore aspects about robotic hands, learning, language, vision and locomotion.

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