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VERSATILE, HIGH-QUALITY MOTIONS AND BEHAVIOR CONTROL OF A HUMANOID SOCCER ROBOT

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Autonomous soccer games represent an extraordinary challenge for autonomous humanoid robots which must act fast and stable while carrying all needed onboard computers, sensors and batteries. In this paper, the development and system integration of hardware and software modules of the 55 cm tall, autonomous humanoid soccer robot Bruno is described to cope with this challenge. Altough based on a "minimalistic" design which only uses gyroscopes in the hip but not foot-ground contact sensors for control of balance, versatile and high-quality walking motions have been developed. Fast forward walking of about 1.5 km/h has been obtained using an efficient sequential surrogate optimization method and walking through uneven terrain with a newly designed passively compliant foot sole. Further modules of the software and control architecture which are needed for an adaptive selection of different motions and autonomous robot behavior are briefly described. Experimental results are reported which have been obtained under the conditions of a live competition. The robot's hardware is mainly based on standard components which can therefore be easily adapted by new designers as no comparable, standard humanoid robot platforms are available.

Keywords: Humanoid Soccer Robots; Humanoid Walking Optimization; Behavior Control.

1. Introduction

The dynamic environment of soccer games represents an extraordinary challenge for the control, stability, speed and versatility of autonomous humanoid robots. In a game vision guided motions which preserve the robot's postural stability must be planned, implemented online and adapted in real-time to the quickly changing environment. Moreover, humanoid soccer robots must carry not only all of their actuators but also all onboard computing, internal and external sensors and energy supplies needed. System design and integration must account for the limited resources in motion, vision, localization and behavior control. Finally, robustness of the overall system is important. A humanoid soccer robot must be able to survive frequent falls without damage and to get up quickly.

During the last decade significant advances in humanoid robotics concerning walking, hardware and software design have been achieved. Motion generation is investigated to imitate human dancing [1]. The humanoid robot *H7* (1370 mm, 55 kg, 35 degrees of freedom (DOF)) [2] is able to execute reaching motions based on the implemented whole body motion. Footstep planning and balancing compensation is used for adaptive walking. The humanoid robot *Johnnie* (1800 mm, 40 kg, 17 DOF) [3] can walk with a maximum speed of 2.0 km/h. The control and computational power is onboard, whereas the power supply is outside of the robot. In the Humanoid Robot Project the robot *HRP-3* (1600 mm, 65 kg, 36 DOF) with special skills for water and dust resistivity is the successor of the *HRP-2* model. This robot can walk with a speed of 2.5 km/h [4]. Additionally several special motions are implemented on the robot, e.g. getting up from lying down [5]. The Korean robot *KHR-2* (1200 mm, 54 kg, 41 DOF) [6] walks with a speed of only 1.0 km/h. The robots *Qrio* (500 mm, 5 kg, 24 DOF) by Sony and *Asimo* (1200 mm, 52 kg, 26 DOF) by Honda are two commercial humanoid robot platforms. *Qrio* [7] can walk stable, jump and run including the transitions between them. It can also execute many special motions, among them coordinated dancing, squatting and getting up. *Asimo* [8] is the humanoid robot with the currently highest speed of 6 km/h and probably the most costly development. Most of these robots are equipped with special sensors for motion execution and control like multi-dimensional foot-ground contact sensors.

The aforementioned humanoid robot projects usually utilize many custom made robot components like motors and drives. Their development is expensive and not affordable to many researchers at universities. Also most of them do not meet all of the initially mentioned requirements for autonomous humanoid soccer robots, especially versatility and robustness. With a relatively low budget the design of robots has to aim at pricy and available standard motor components combined with a suitable suite of sensors, computational units and software. A testbed for such humanoid robots is RoboCup, a yearly organized competition for autonomous robot soccer. Since the start of this competition for humanoid robots in 2001 not only the number of participating teams has increased every year. Also the soccer games have become more dynamical as the robots are able to move more stable and efficiently and to utilize a large variety of walking and special motions. Using advanced software and control architectures the humanoid robots are able to navigate, to react on changes in the dynamic environment and to plan their behavior.

In this paper the development and system integration of hardware and software modules for a powerful, autonomous humanoid soccer robot with versatile and high-quality motions and behaviors is described. It is organized as follows:

Section 2 introduces the hardware components for motion, sensing and onboard computing and their development to obtain a robust and versatile autonomous humanoid robot platform. Section 3 describes the distribution of the computational power to a microcontroller and a lightweight onboard computer. The realization of versatile motions is outlined in Section 4 and the corresponding software architecture and behavior control in Section 5. A selection of results is presented in Sects. 4.2 and 5.3. It should be noted that these have been achieved under the conditions of a live competition at RoboCup 2006 and not in a controlled lab environment. Further information including videos of results can also be obtained from the websites `www.dribblers.de` and `www.hajimerobot.co.jp`. An outlook is given in Section 6.

2. An Autonomous Humanoid Soccer Robot Platform

The challenge of realizing fast and stable autonomous biped walking requires motors with relatively high torque combined with relatively low body and payload masses for facilitating postural stability [9]. For autonomous humanoid robots all onboard components must be selected very well with respect to as small as possible masses and energy requirements to reduce the overall weight of the payload including the batteries.

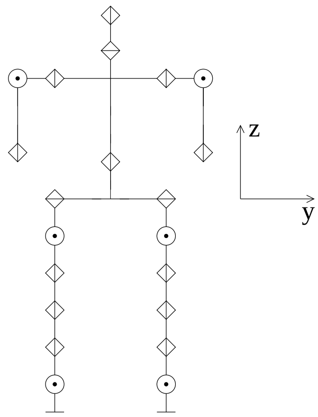


Fig. 1. The 55cm tall, autonomous humanoid robot Bruno (left) which is based on the Hajime Robot HR18 and its kinematic structure (right).

The autonomous humanoid robot Bruno presented in this paper is 55 cm tall, has a total mass of 3.3 kg and consists of 21 actuated rotational joints, 6 in each leg, 3 in each arm, 1 in the waist of the upper body and 2 in the neck. The robot kinematics is depicted in Fig. 1. The height of the center of mass (HCM) is 25 cm. According to the design rules of the RoboCup Humanoid League the maximum area of one foot is limited depending on the HCM. The foot area of one foot of Bruno is only 123 cm^2 which is relatively small compared with the total height of the humanoid robot. The robot is designed in a lightweight manner. The links of the robot consist of tailor made aluminium parts because of the good relation between stiffness and weight. In the upper body lightweight carbon fiber reinforced plastic is used for the holder of the onboard computer. The selection of standard motors benefits from the ongoing fast progress in the development of powerful small servo motors. 19 joints are actuated by the servo motor DX-117 by Robotis (34 kg-cm, 67 g) which is used as standard motor of the robot. In the two knee joints where especially high loads occur the stronger, but also heavier, newly developed high-torque motors RX-64 (67 kg-cm, 125 g) from Robotis are used. For the two neck joints less powerful motors would be sufficient. However, less powerful and more lightweight motors than DX-117 with the same physical bus and digital communication protocol as DX-117 and RX-64 were not available. Having the same communication protocol for all motors facilitates robot development and its modularity. Furthermore, the selected actuators not only provide information about position and speed but also internal temperature and input voltage which enables research in a wide range of control strategies for locomotion and postural stability. In the robot hardware design phase, the measurements of the motor temperature had revealed the weakness of the previously used DX-117 motors in the knees for permanent and fast walking. Initial design experiments with the stronger RX-64 motors for all actuated joints indicated that the stronger but heavier motors would not pay off for faster walking because of the larger total weight of the humanoid robot. Another initial robot design contained three more actuated joints, one more motor in each arm and one in the waist for turning about the upwards directed axis (see also [10]). As all relevant motions of the upper body and the arms like standing up from lying on the back or front can be realized with suitable link length without these extra servos they have been removed to further reduce the overall weight of the robot and to improve walking speed and stability. The robot is powered by two 14.8 V batteries for the motors which are placed onto the feet and a 7.4 V battery for the controller board which is attached to the hip.

For inertial sensing the robot is equipped with three one axis gyroscopes SSSJ CRS03-04 used for improving postural stability and a three axes accelerometer Crossbow CXL04LP3 used to detect if the robot has fallen down and to which side. These sensors are mounted at the left and right side of the hip frame. It is shown in Sect. 4 that fast and stable walking can be obtained with such a ”minimalistic” sensor suite and does not require to use foot force sensors.

The computing and information processing system of the robot consists of several layers. Hard real-time requirements for servo motor control are handled on a microcontroller and soft real-time tasks on an onboard computer (see Sect. 3). The development of software and components for sensory perception must match the combination with a light onboard computer with comparatively low computational power and energy consumption (Sect. 5).

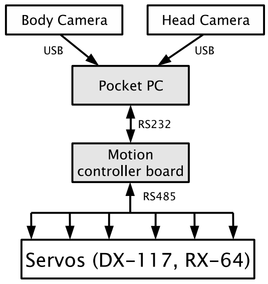


Fig. 2. Flow chart of data stream in the semi-distributed, hierarchical computing system.

Robot vision is realized by means of two off-the-shelf CCD cameras (Philips ToUCamPro) with different lenses. The cameras come with a plastic cover, which is robust and lightweight. The articulated head camera offers a (horizontal) angle of view of 45 deg and is used for the perception of small objects like the ball and field lines. The chest camera is attached to the upper body and is used to obtain a peripheral view of the environment with an angle of view of about 95 deg (cf. Sect. 4.5). In combination the two cameras offer a binocular, variable-resolution view of the robot's environment and a human-oriented embodiment [11]. The wide angle camera incorporates some of the properties of peripheral vision of the human eye used for approximate orientation and localization whereas the narrow angle head camera can localize and track objects like the ball much farther away, thus mimicking properties of the more focusable inner area of the human eye.

3. Hierarchy of Computing and Information Processing Layers

In the current robotic system the computational power for information processing is distributed into basically two, respective three, layers. The flow of information in this distributed system is shown in Fig. 2.

The lowest, third layer of computation is performed within the 21 servo motors. Each servo motor is equipped with some "intelligence" consisting of adjustable controllers for the joint's position and velocity which operate at a constant rate of about 1 ms (estimate). The motors are also able to monitor their operational environment, e.g. temperature of the motor as well as voltage of the power supply, thus allowing autonomous emergency shutdown in case of overheating motors or discharged batteries.

For information processing and feedback control on the "reflex layer" a micro-controller board with a Renesas SH7145 32-bit processor running at 50 MHz and 1 MByte of RAM for the generation of humanoid leg and arm motions by coordination of multiple joints is applied. The servo motors are connected via a RS485 bus to the controller board. At a constant rate of every 10 ms new set-point positions are generated using the methods described in the follwing section and sent to the servo motors. The microcontroller is also used to collect and evaluate data from the inertial sensors of the robot. It is connected to the main CPU of the system using a RS232 connection running at 57.6 bits/s. The microcontroller is programed in C using GNU compiler GCC as a cross-compiler. The binaries are transfered to the microcontroller using the freely available flash development toolkit from Renesas.

On the "cognitive layer" the computations for vision, localization and behavior control as well as wireless communication are performed on an off-the-shelf Pocket PC with a Intel PXA272 processor with 520 MHz, 128 MB SDRAM, 64 MB Flash ROM and integrated power supply. The operating system is real-time Windows CE. The Pocket PC is equipped with a display and touch screen which enable some onboard debugging, serial USB (host and client) and RS232 interfaces as well as wireless LAN. The two cameras are connected to this onboard computer via USB.

4. Humanoid Motions

Basic properties of bipedal walking, postural stability and their realization have been the subject of intensive research in the last decades, e.g. [12]. In this paper we describe a "minimalistic" approach to stable, fast and versatile humanoid walking without the need for foot-ground contact force sensors and with remarkable performance considering the full autonomy of the robot's hardware made of standard components and with all required computing, sensing and energy supply onboard.

4.1. *Control of balance*

The request for a certain walking motion by coordination of the robots leg, waist and arm joints is sent by the Pocket PC to the motion controller board, where the adequate gait is selected. Based on this gait request the calculation of the leg joint trajectories for a walking motion is computed online on the microcontroller board by an inverse kinematic model of the legs. During a stride both feet follow a precalculated trajectory. As shown in Fig. 1, the x-axis is directed forwards, the y-axis is directed sidewards, and the z-axis is directed upwards. The resulting trajectory of the swinging foot for the (x, y, z)-axes is shown in Fig. 4 for a half stride discretized using n time steps. The value of n depends on the time length of the specific stride. A constant number of 100 time steps per second is used.

The trajectory for the standing foot is obtained as follows. The (x, y)-trajectory of the projected Center of Mass (CoM) is calculated in such a way, that the Zero Moment Point (ZMP) is inside the convex hull of the area of the one foot, respectively two feet, currently touching the ground. If the ZMP condition holds for y, the motion equation

$$m \cdot \ddot{y}(t) \cdot h + m \cdot g \cdot (y_{ZMP} - y(t)) = \tau \qquad (1)$$

simplifies to $\tau = 0$ with m denoting the mass of the simplified robot, y the position in sidewards direction, h the height of the center of gravity, g the gravity and y_{ZMP} the desired position of the ZMP (cf. Fig. 3). Eq. (1) results in

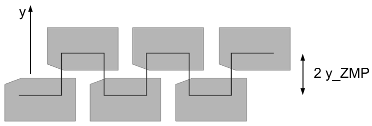


Fig. 3. The desired ZMP position y_{ZMP} (solid line) during a walking motion. The ZMP is kept within the convex hull of the ground contact points.

$$y(t_i) = C_1 \cdot e^{\sqrt{\frac{g}{h}} \cdot t_i} + C_2 \cdot e^{-\sqrt{\frac{g}{h}} \cdot t_i} + y_{ZMP} \tag{2}$$
$$\text{with } C_1 = -y_{ZMP} \cdot \left(e^{\sqrt{\frac{g}{h}} \cdot \frac{T}{4}} + e^{-\sqrt{\frac{g}{h}} \cdot \frac{T}{4}} \right)^{-1}, \quad C_2 \;=\; C_1$$

and with T denoting the time for a full stride and t_i the discrete time steps for a full stride with $i = 1, \dots\ 4n$. Now the trajectory y_{traj} of the swinging leg is calculated with $y(t_i)$ from Eq. (2) by

$$y_{traj}(t_i) = y(t_i) - \frac{h}{g} \cdot \ddot{y}(t_i) \tag{3}$$

for a discrete time t_i for the first half of a half stride, cf. Fig. 4(b).

The trajectory of the standing leg is calculated in a similar manner. The hip is moving along an S-shaped trajectory and during a step both feet keep the same distance on the y-axis.

When the robot is walking with constant speed, the ZMP in direction of x is 0 and can be neglected. The trajectory x_{traj} is given by linear interpolation

$$x_{traj}(t_i) = \frac{i}{n} \cdot x_{dist} \tag{4}$$

from 0 to x_{dist} which is the maximum distance of the hip to the standing leg respectively the swinging leg in x direction for a full stride, cf. Fig. 4(a).

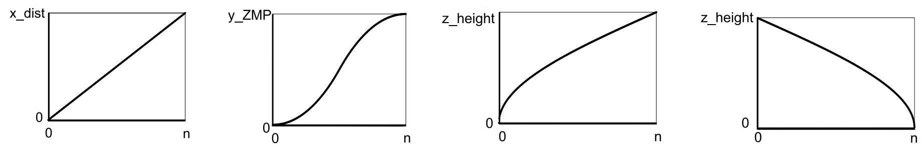
The trajectory of the swinging leg in z-direction is calculated in a different manner for upward and downward motion. To reduce the influence of the ground error, the slopes of the curves are high close to the ground, e.g. in the upward motion at the beginning and in the downward motion at the end of a step. The trajectories (cf. Figs. 4(c) and 4(d)) are given by

$$z_{traj\_up}(t_i) = \frac{z_{height} \cdot c_4}{\pi} \left(\frac{\pi}{2} - \arcsin\left(1 - \frac{i}{n}\right) - c_3 \right) \tag{5}$$

$$z_{traj\_dw}(t_i) = z_{traj\_up}(n - t_i) \tag{6}$$

with z_{height} denoting the maximum desired height of the foot in z direction and $c_3 = 0.75$, $c_4 = 8$ appropriate constants. For the standing leg, the z-value is defined to be constant.

The set-points for the joint angles of the swinging and of the standing leg are calculated based on these trajectories considering a constant angle of the hip in z-direction and the condition, that the foot-sole is parallel to the (even) ground.



(a) x_{traj} (b) y_{traj} (c) z_{traj_up} (d) z_{traj_down}

Fig. 4. (x, y, z)-trajectories of the reference point of the foot for a walking motion which is mapped to leg joint angle trajectories using the inverse kinematics model of the leg. The reference point is the point where the last ankle joint enters the foot sole.

The walking motion is stabilized using the data from the gyro sensors at the hip. For this purpose the previously obtained set-points q for the joint angles are superimposed by corrections from the gyroscope controller

$$q_{new} = q + k_p \cdot \omega + k_d \cdot \frac{d\omega}{dt} \tag{7}$$

with q respectively q_{new} representing the angles in foot pitch, foot roll, hip pitch, hip roll, waist pitch, shoulder roll and shoulder pitch, cf. the kinematic structure in Fig. 1, right. The angular velocity measured at the hip along the y-axis is denoted by ω and the time by t. The control parameters k_p and k_d have to be selected appropriately for the specific robot based on experiments. The interaction of the functional modules of motion generation is depicted in Fig. 5.

The improvement of postural stability achieved by the gyro controller was investigated for three different settings experimentally: (i) the transition from standing to walking, (ii) permanent, mostly straight walking at a speed of 40 cm/s and (iii) during an autonomous soccer game. In all experiments of the transition (i) from standing to walking motion the robot never falls down with active gyro control, but in about 65 % of several dozen experiments without active gyro control the robot fell down backwards.

During each of the experiments (ii) with permanent, mostly straight, walking motion, the robot walks stable along the field with activated gyro control for at least 5 min in a row. Without gyro control the robot wobbles heavily at the high walking speed of 40 cm/s. This effect causes strong, additional strain on the motors resulting in an unwanted motor overheating. This is followed by an emergency shutdown of the respective motors which results in a fall down of the robot unless it has not already fallen down because loss of postural stability. In nearly all experiments the robot was fallen down within the first minute of fast walking without gyro control.

As a representative basic soccer scenario for (iii) approaching and positioning towards the ball and kicking it was selected. Without the gyro control the robot fell down in most experiments because of the high accelerations of the upper body which are caused by the numerous motion changes like walk, turn, stand and kick and which could not be compensated.

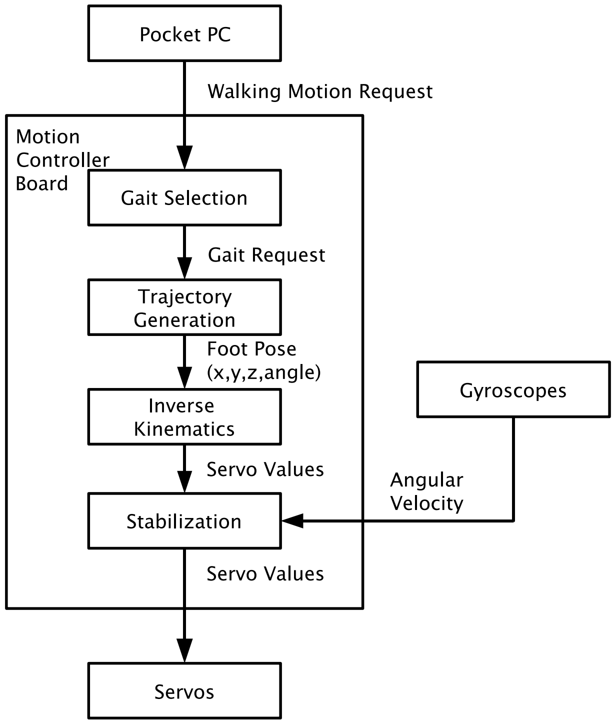


Fig. 5. Structure of the functional modules for walking motion generation. Requests for humanoid robot motions like standing, accelerating, walking at a certain speed, turning, kicking etc. are made by the robot's behavior control running on the onboard computer. They are processed in a series of steps on the motion controller board. After selecting an appropriate gait for the requested motion, the trajectory for the feet soles are generated using ZMP theory. Using inverse kinematics of the leg, the required set-point trajectories for the involved joint angles are computed. Walking stability is improved by correcting the joint angle set-points depending on inertial sensor data.

4.2. *Optimizing walking speed*

Humanoid robot soccer represents an extraordinary challenge for the development of versatile and stable motions. During a game fast motions are required which preserve the robot's stability and can be adapted in real-time to the quickly changing environment.

Different approaches exist for optimizing the walking motion of humanoid robots. During the 1990s trajectory planning methods and model-based control methods relying on nonlinear robot dynamics models have evolved into the state-of-the art for developing and implementing fast and accurate motions for industrial robots. Successful control of the nonlinear robot dynamics may also be the key to fast and stable bipedal robot motion, e.g. [13]. Application of these methods requires the development of a sufficiently accurate dynamic model of the humanoid

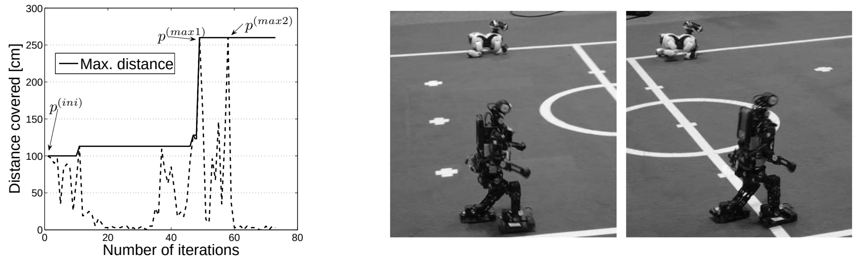


Fig. 6. Left: Progress in the objective function during walking optimization. Right: The fastest humanoid robot keeps pace with the optimized walking speed of a Sony AIBO in a live demonstration at RoboCup 2006.

robot with respect to kinematical and kinetical data like masses, center of masses and inertias of links and joints and of the motor and gearbox properties. Also efficient methods for modeling the tree-structured multibody system dynamics of humanoid robots and for solving the resulting high dimensional, nonlinear optimal control problems for optimal robot motion are required, e.g. [14,15]. A benefit of this approach is that it does not wear out expensive humanoid robot hardware as it does not need many physical experiments. A drawback is that the required data is not easy to obtain. Good estimates of kinematical and kinetic robot data may be obained from CAD data. However, effects like gear backlash and joint elasticity which may depend on operational conditions like time and temperature as well as varying foot-ground contacts make it difficult to derive a highly accurate model of the humanoid robot dynamics.

An alternative is to use physical walking experiments to precisely evaluate the real robot's behavior for optimization. Then two major problems arise. First, the objective function to be minimized, e.g. the time needed to walk a certain distance, is noisy and non deterministic as every two experiments with exactly the same parameter and control setting always yield (at least slightly) different results. Therefore robust optimization methods like genetic or evolutionary algorithms[16], pattern search, policy gradient learning or particle swarm optimization methods[17] must be applied. However, these methods require up to several thousands of walking experiments, e. g. [17], which may lead to a significant wear out of the humanoid robot.

A new, less time and hardware consuming approach is investigated here. The sequential surrogate optimization approach [10] is based on a stochastic approximation of the objective function. It is applied in an iterative process of walking experiment, improvement of a smooth response surface and its very fast optimization using efficient Newton-type optimization methods. The computed minimizing (or maximizing) parameter set serves for the settings of the next walking experiment, and so on.

Before application of the method a suitable formulation and set-up of the optimization problem is needed. Five parameters have been selected for optimization which enter the trajectory generation in the walking motion generation described in Fig. 5. These are the relation of the distances of the front and of the rear leg to the center of mass, the roll angle of the foot and its height above the ground during swing phase, and the pitch of the upper body.

In the walking experiments Bruno starts from standstill with a small stride length of 110 mm which is increased every two steps by 5 mm up to a maximum of 240 mm length at a constant frequency of approximately 2.85 steps per second. The quality of the current parameter set is measured by the distance the robot travels with 52 steps. Falling of the robot is returned as an objective value with very large penalty to the sequential surrogate optimization method.

The initial parameters for the iterative optimization procedure orginiated from a hand-tuned walking gait of about 10 cm/s. After only 74 walking experiments which had been performed in about a half day the optimization process was terminated with an obtained maximum walking speed of more than 40 cm/s and a covered distance of more than 260 cm (cf. Fig. 6 left).

Bruno was the only humanoid robot participating in demo footraces against several four-legged Sony AIBO robots at RoboCup 2006. The humanoid robot was able to keep pace with the highly optimized walking of the four-legged robots (see Fig. 6). With an average speed of more than 40 cm/s Bruno reached a fifth place among the seven participants. In a second demo race it outran the two finalists of the footrace competition from the taller teen-size humanoid class. Please note that these experiments were performed in a live competition and not in a controlled lab environment.

Multidirectional walking. To achieve a suitable position and orientation for kicking the ball towards the goal without long-standing positioning in front of the ball, the robot walks multidirectional to the desired pose. A superposition of turning and forward-walking motion is used for this purpose. During walking motions the joints of each leg are used for different purposes (cf. robot kinematics in Fig. 1 right). The first, uppermost joint is used to turn the leg around the upward-axis, joints two and six are used to shift the robot's hip sidewards and joint three to five are used to move the feet forward/backward and upward/downward. When walking forward or sideward, only joint two to six are utilized. For turning on the point or walking in curves aditional turning motions are generated by the first joint during the swinging phase of each leg.

4.3. *Walking on uneven terrain*

Today most humanoid robots are not able to walk on a terrain which has not been modelled in advance. Walking over uneven terrain is still an open and not thoroughly investigated field of humanoid robots. For example, in [18] a walking control for uneven terrain is introduced which is based on posture control and

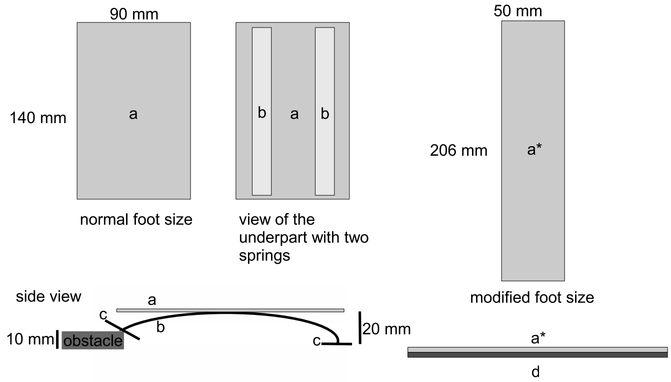


Fig. 7. Two different foot design for walking on a rough terrain. In the left design, two springs (b) are attached on the foot plate (a). On each spring, two moveable plates (c) are mounted to avoid stumbling. In the right design, the foot (a*) is enlarged in the length and shortened in the width. On the underpart, a soft material (d) is added.

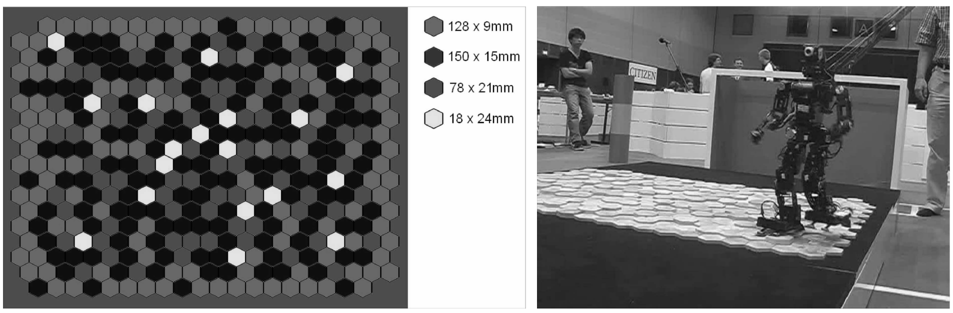


Fig. 8. Left: Example layout of the 1.5 m×1m large uneven terrain and the number and heights of the different hexagonal components. Right: Bruno walking the uneven terrain with the passively compliant foot sole.

absolute motion estimate with newly developed attitude measurement sensor and center of pressure control for each foot for realizing stable contact to the terrain. Implemented on a HRP-2 robot an uneven terrain consisting of rectangular plates of 14 mm thickness could be passed.

In this paper we present a different, rather "minimalistic" approach to walking on uneven terrain without using foot-ground contact sensors. A passively compliant foot sole has been designed which enables the humanoid robot Bruno to walk over a very unregular, uneven terrain with height differences of up to 15 mm only by using the posture control described in Sect. 4.1 and an appropriate gait selection.

The new, passively compliant foot sole design is depicted in Fig. 7 (left) and was developed by [19]. Two springs (b) are attached to each foot (a), each one parallel to the long side of the foot plate. Thus, contact with the ground occurs at the fore-tips of the springs. Each contact point is extended by a small, movable plate (c) which is heavier on the back side to avoid getting stuck at a discontinuous ground level during forward walkin. Irregular uneven terrains with up to 15 mm height could be walked through in experiments. For example, in a live demonstration at RoboCup 2006 the irregular, uneven terrain of 1 m depicted in Fig. 8 (left) was walked through in about 45 s. For this purpose, sequences of, e.g. 8, short steps of step length 5 cm and duration 0.8 s with intermediate breaks of about 1.5 s of standstill have been applied. It should be noted that walking on even terrain is also possible but not in the same speed as with a flat feet sole (Sect. 4.2).

Whereas the passively compliant foot sole based on springs enables versatile walking over a wide variety of terrains a second foot modification has been developed which is tailored to the specific uneven terrain of Fig. 8. The base foot shape (a^*) is extended in the forward direction to a length of 206 mm and narrowed in the sidewards direction to a length of 50 mm to satisfy a given upper limit on the total foot area. To absorb the impact of landing a compliant material (d), in this case a sponge, is attached under the foot. With this tailored modification and the gyro control for postural stability, the robot was able to walk over the field in 7.5 s using a very low stance and fast steps of about 6 cm length and 0.25 s duration.

4.4. *Other humanoid motions*

In an autonomous soccer game of humanoid robots many other motions are needed. These include a variety of kicks for different game situations, jumping and ball blocking motions for the goal keeper as well as motions to get up from a fall. Such motions are developed in advance via teach-in methods and implemented as set-point trajectory tracking control on the joint level.

An adequate kick is selected from 19 available kicking motions, depending on the position of the ball (in front of left or right foot), view angle and distance to the goal, and the validity of the self localization of the robot (e.g. Fig. 10). These parameters are obtained via a world model given in the control architecture and evaluated in the hierarchical behavior state machine (Sect. 5.2).

A suitable getting up motion is initialized by the accelerometer values indicating that the robot has fallen down and to which side. Stable getting up motions for the robot lying on the back as well as on the front have been implemented. The motions are inspired by human motions.

4.5. *Motion of the camera head*

The motion of two motors of the pan-tilt neck can be controlled separately from the whole body motion to enable a directed viewing to special objects of interest. The current programming contains among other a ball search-and-follow mode with respect to the current whole body kinematic and a self localization mode for searching points of interest for self localization in the humanoid soccer field.

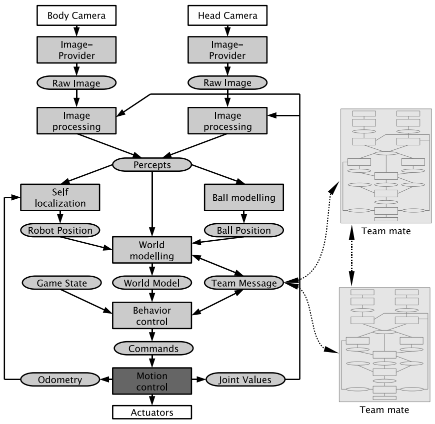


Fig. 9. Overview of modules (rectangles) and exchanged messages (ellipses) of the control software. White blocks denote sensors or actuators and light gray blocks modules executed on the Pocket PC. The dark gray block is executed on the microcontroller board.

5. Software and Control Architecture

5.1. *Control architecture*

The control software consists of several modules for the different tasks [20] (Fig. 9) is implemented in object oriented C++. Based on the images from the two directed cameras, objects of interest (the ball, goals, poles, field lines, line crossings and obstacles), the so-called percepts, are detected. The image processing is done separately for both cameras at different frame rates, depending on the camera and the current role of the robot varying between 1.5 Hz and 4 Hz (body and head of striker) and 7 Hz (head camera of goalkeeper). Higher rates of image processing are not possible because of the very limited onboard computing power available on the Pocket PC. The percepts are time-stamped and used for modeling of the environment. The control software contains a Kalman filter for ball modeling and a Markov localization with particle filtering [21] for self localization.

Bruno shares his world model with the other team member(s) via UDP broadcast to achieve a fast communication. To obtain information about the current state of the game, the robots receive UDP broadcasts sent from an external computer running a referee software.

5.2. *Behavior control*

The behavior module has to control the actuators based on the described input supplied by the world model. These decisions are described in the Extensible Agent Behavior Specification Language (XABSL) [22] as a hierarchy of finite state machines.

To access the information that is needed to decide on the best action, symbolic representations (the so called *input symbols*) are used. To integrate the XABSL Engine into the control software, a set of symbols which make the information of the world model accessible has been implemented. Each state machine is called an *option*. An option consists of multiple states and describes the state transitions based on the available input symbols. Every state has either a *subsequent option*, which is evaluated when this state is active, or specifies how to control the actuators which is called a *basic behavior*. The linked options of a behavior form a tree with basic behaviors at the leafs. In every execution cycle the options in the tree are traversed starting at the root option. The path along the tree of options to the basic behavior is called the *activation path*. Each time the world model gets updated the XABSL behavior is executed, which allows fast adaption to changes in the environment.

The discrete state transitions are well suited when realizing high-level long-term behavior decisions or low-level discrete decisions, e.g. performing a special action like a kick. But they are not well suited when a continuous behavior like walking to a position while avoiding obstacles is needed. Such continuous behavior can better be realized as complex basic behavior for example using a potential field.

The behavior for choosing the best kick is implemented in one option. The specific parameters of all kicks, covering the relative ball position and the direction and speed of the kicked ball, must be determined and incorporated into this option manually. Based on the desired kick direction and speed the appropriate kick is chosen by the decision tree of the option. If no kick is possible in the current situation the decision tree chooses a walking motion to achieve a better position of the robot to the ball.

5.3. *Experimental results*

Backheel kick. In a live game of the penalty kick competition at RoboCup 2006 the robot approached the ball with the opponent goal directly behind. The robot could not see the opponent goal anymore because of the directed vision, but the self localization was aware about the position and orientation on the field. Therefore the behavior decided to kick the ball with a special backheel kicking motion (as illustrated in Fig. 10) and scored a regular goal. To the authors' knowledge it was for the first time that a backheel kick was performed by a humanoid robot which additionally was rewarded by a goal in the autonomous robot soccer competition.

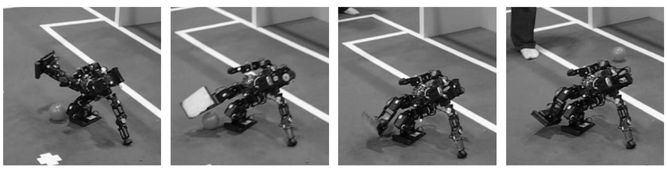


Fig. 10. Bruno scoring a goal by performing a backheel kick.

Cooperative team behavior. Not only versatile motions of one autonomous humanoid soccer robot are required in a game but also cooperative team behavior. The robot behavior uses the communicated information of the teammate to decide the dynamic role during game. In Fig. 11 an example is given from a live competition game at RoboCup 2006 where both robots approached the ball. Based on the communicated distance of each robot to the ball and the other robots role each robot decides its own role. The robot with the role "striker" continues to approach the ball while the "supporter" steps back and moves to a supporting position thus avoiding the obstruction of its own teammate.

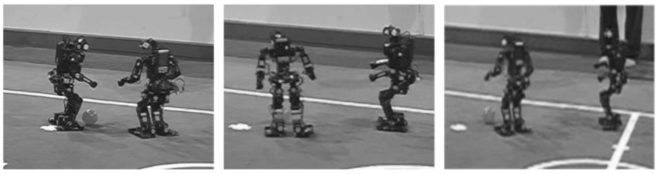


Fig. 11. Cooperative team behavior during the 2 on 2 humanoid robot soccer game for 3rd place at RoboCup 2006: Both robots detect the ball, the left robot is closer to the ball, gets the role "striker" and continues to approach the ball while the right robot obtains the role "supporter" and steps back.

6. Conclusions

In this paper the development of the hardware and software components and their integration into the 55 cm tall, humanoid soccer robot Bruno have been described. The robot's hardware is mainly based on standard components which can therefore be easily adapted by new designers. In a soccer game of autonomous humanoid robots Bruno has to carry all onboard computing, sensors and energy supplies needed. Nevertheless, a variety of high quality motions have been demonstrated under the conditions of a live competition at RoboCup 2006 including the fastest forward walking ability, the first-ever backheel kick of a humanoid robot and walking through uneven terrain. These versatile, high quality motions have been achieved by a "minimalistic" control approach which only relies on postural stability using gyros in the hip but not foot-ground contact sensors.

Control of individual robot and team behavior for autonomous robot soccer playing capabilities were realized using a hierarchical state machine. Information about the current state of the dynamic environment during soccer games is obtained by processing the information by two directed cameras, one articulated narrow-angle camera in the head and one wide-angle camera in the chest. The robots described in this paper are the only humanoid robots of the top three teams at RoboCup 2006 which used directed and not omni- or circumferential type vision for perception and localization.

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