Versatile, high-quality motions and behavior control of humanoid soccer robots

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***Abstract*— Many different and high-quality humanoid motions have been developed based on a tailored, 55cm tall humanoid robot kinematics and design using 21 servo motors and inertial sensors for stabilization. These include fast forward walking of about 1.5 km/h in permanent operation, multidirectional walking capabilities, a variety of standard and spectacular kicks, standing up motions as well as motions displaying an emotional state of the robot. While all robot motions are executed in real-time on a controller board an adaptive selection of different motions and autonomous robot behavior are controlled by hierarchical state machine executed on an onboard Pocket PC. Information about the current state of the dynamic environment in a soccer game is obtained from two directed cameras with wide and narrow angles. During RoboCup 2006 the robot demonstrated the fastest walking of all kid- and teen-size humanoid robots on regular terrain as well as in the rough terrain challenge. Also a large variety of different motions as well as individual and team behaviors during successful autonomous soccer games have been demonstrated including the scoring of a goal with the first autonomously performed backheel kick of a humanoid robot.**

Keywords: humanoid robot design, fast humanoid robot walking, whole body humanoid robot coordination, autonomous behavior control

I. Introduction

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 [17]. The humanoid robot *H7* (1370 mm, 55 kg, 35 degrees of freedom (DOF)) [18] 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) [14] 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 [11]. Additionally several special motions are implemented on the robot, e.g. getting up from lying down [10]. The Korean robot *KHR-2* (1200 mm, 54 kg, 41 DOF) [12] 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* [16] 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* [9] is the humanoid robot with the currently highest speed of 6 km/h and the most costly development. Most of these robots are equipped with costly high tech sensory for the motion execution.

All of these projects have in common that the development is expensive and the hardware of the robots consists not of off-the-shelf components, but of tailored parts developed for this robot. Thus robot projects are only affordable with a good funding, not available for a wide variety of universities. With a low budget the design of robots has to aim to cheap and easily available components, combined with tailored sensors, computational units and software. A testbed for such robots is the RoboCup, a yearly organized competition for robot soccer. This event offers a scenario for autonomous humanoid robots and requires fast walking and autonomous onboard control to compete in a dynamical environment. Since the start of this competition for humanoid robots in 2001 more teams participate each year, the soccer games get more dynamical as the robots move more actively, react with an elaborated software in a better way on their environment and partially plan their behavior. So the focus moves from pure construction and basic motions to more sophisticated hardware and motions to be able to compete with the others. These challenges are met with a tailored hardware for humanoid robots and a large variety in walking and special motions, combined with an advanced software and control architecture. Regarding a robust hardware most of the teams in the Humanoid League use adapted servo motors for the construction with different types, where a higher torque of the motor is needed, e.g. [2], [21]. However, beside the mere motor selection also the generation of the motions has to be capable to utilize the torque of the motors. Similar requirements also exist for the control architecture, especially the behavior control. They must be adapted to the hardware of the robot. As all the teams are meanwhile equipped with adequate cameras for perception as main sensor, the robots walk directed to the ball and kick it. In one of the competition, the 2 versus 2 game, two field player can interact with each other to play in a team with dynamic role assignment. Although several teams use a finite state machine [4], which enables in general the possibility for a modular dynamic behavior control, only few teams could

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show the application of a high-level behavior control, which is essential to show a good performance.

In the RoboCup 2006 we could fulfill the before mentioned needs. We presented the fastest walking humanoid robot of all participating robots in KidSize as well as TeenSize and showed a variety of special motions, not only for kicking, but also for getting up from the floor or emotions, the latter mainly for amusement of the audience. With a modular hierarchical finite state machine with monitoring and controlling facilities a high-level behavior could be developed, which can select quickly useful motions based on the perception of the environment.

The paper is organized as follows: Section II introduces the hardware and modification done to manufacture a robust versatile robot platform. Section III describes the distribution of the computational power on a microcontroller and handheld. The variety of motions feasible with the hardware design is detailed in Section IV with the belonging software in Section V-B. The results achieved in RoboCup 2006 are presented in Section VI. Further information can also be obtained on our website `www.dribblers.de` and `www.hajimerobot.co.jp`. An outlook to future work is given in Section VII.

II. TAILORED ROBOT PLATFORMS

The challenge of autonomous biped walking requires high torque motors combined with low mass for keeping balance in an optimal way [20]. The low additional payload causes all on board components to be well selected with respect to small mass and as less as possible additional energy supply to reduce the mass of the required batteries. The presented humanoid robot (see Figure 1) has a total mass of 3.3 kg at 55 cm total height and center of mass in 25 cm height. The foot area of one foot is only 123 cm^2, which is small compared with the total height of the robot. It is designed in a lightweight manner, which refers to mainly small robotic systems with a small additional payload and the requirement of stabilizing locomotion dynamics using inertial sensors like gyroscopes and accelerometers. 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.

The herein described robot is equipped with altogether 21 non-redundant servo motors, 6 arranged in each leg, 3 in each arm, 1 in the upper body and 2 in the head. The motors are tailored for the challenge of fast walking: The knees, which are highly stressed, are equipped with the newly developed high-torque motors RX-64 by Robotis (67 kg-cm), the other motors are the conventional servo motors DX-117 by Robotis (34 kg-cm), often used in humanoid robots.

Besides providing information on the current position, the servos also are able to measure the current temperature and other parameters and provide these informations to the control application. Due to measurements of the temperature action, the previous used DX-117 motors in the knees could be diagnosed to be too weak for fast walking motions and could be replaced.

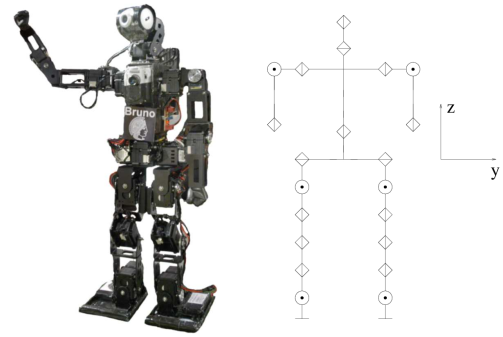


Fig. 1. The 55cm tall, autonomous humanoid robot Bruno (left) which is based on the Hajime Robot HR18 and its kinematic structure (right).

The robot is extended with two off-the-shelf CCD cameras with different lenses, which can be run with different frame rates. The cameras come with a plastic cover, which is robust and lightweight. The articulated head camera offers a view angle of 45 deg to enable the perception of small objects, whereas the fixed mounted body camera gives a peripheral view of the environment with a angle of 95 deg. In combination the two cameras offer a binocular, variable-resolution view of the robots environment according to a human-close embodiment [1]. The wide angle camera incorporates some of the properties of the outer area of the human eye like a rather blurred recognition of shapes. Where as the narrow angle head camera can localize objects like the ball much farther away, thus mimicking the more focusable inner area of the human eye.

In contrast to many other humanoid robots this robot is not equipped with expensive sensors as foot force sensors, but can walk robustly with a minimal set of sensors: A three axes accelerometer and three one axis gyroscopes are applied as inertial sensors on a rate of 100 Hz and used for stabilization during walking motions by correction motions mainly in the arms and detecting the toppled robot.

The control software is executed 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 a real-time Windows CE. Further on the Pocket PC is equipped with a display and touch screen to enable on board debugging, serial USB (Host and Client) and RS232 interfaces as well as wireless LAN.

Additionally, the robot is provided with a micro controller board with a Renesas SH7145 32-bit processor running at 50 MHz and 1 MByte of RAM for the motion generation. These two systems are separated to meet the requirements of real time motion execution. For further details on the computing components see Section III.

The robot is powered by batteries with 14.8 V for the motors and 7.4 V for the controller board. The motor batteries are placed in the feet to lower the center of mass of the robot.

The robot frame partly consists of aluminum used in the legs, arms, and head holder and partly of carbon fiber reinforced plastic used in the upper body. The metal was chosen to give a basic stability, whereas the plastic reduces the weight in less stressed parts.

Further modifications of the first robot version with 24 motors towards a more lightweight upper body have been the demounting of one of the originally four motors in each arm and one of the originally two motors in the waist, which was used for turning about the upwards directed axis, in the upper body (see also [8]). The reduced degrees of freedom of the robot, e.g. for standing up from lying on the back or front, have been compensated by modified motions, so no loss in mobility appeared. For soccer playing applications, the front of the robot's feet has been prepared with a flat, wooden material to enable hard, directed kicks. As goalkeeper the robot has been equipped with glove like rubber foam protectors to decrease the impact on the arm motors when diving for the ball.

III. Semi-distributed System

In the current robotic system the computational power is distributed into several layers. The lowest level of computation is performed within the 21 servos. Each servo is equipped with considerable "intelligence". Besides controlling the position of the joints with adjustable control parameters, the servos are able to monitor their operation environment, e.g. temperature of the motor or voltage of the power supply, thus allowing autonomous emergency shutdown in case of overheating motors or discharged batteries.

The servos are connected via a RS485 bus to the controller board. Every 10ms new desired positions are generated using the methods described in the next section and sent to the servos. Further the controller is used to gather and evaluate data from the inertial sensor of the robot. The controller is connected to the main CPU of the system using a RS232 connection running at 57.6 bits/s.

The higher level computations like vision, localization, behavior control and wireless communication are performed on an Acer n50 Premium Pocket PC. The cameras are connected to this device via USB. The flow of information in the distributed system is shown in Figure 2.

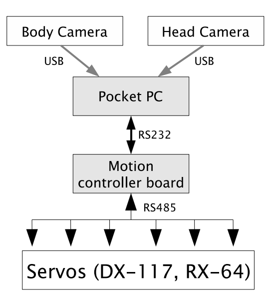


Fig. 2. Flow chart of information data stream in the semi-distributed system.

IV. Motions

A. Humanoid Locomotion

The base motion of biped robots, namely walking, has been highly investigated throughout the last decade because of the challenging requirements. We analyzed several different aspects of humanoid walking in theory and could verify them in experiments.

a) Balancing: The request for a walking motion 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 trajectories for a walking motion is realized by an inverse kinematic model, which is executed on the micro controller board in the upper body of the robot. During a stride both feet follow a precalculated trajectory.

As shown in Figure 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 Figure 4 for a half stride discretized in n time steps. The generation of the trajectory for the standing foot is described in the text.

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 foot respectively feet touching the ground.

If the ZMP condition holds for y, the motion equation

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

simplifies to

$$m \cdot \ddot{y}(t) \cdot h + m \cdot g \cdot (y_{ZMP} - y(t)) = 0 \qquad (1)$$

with m 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 (see Figure 3).

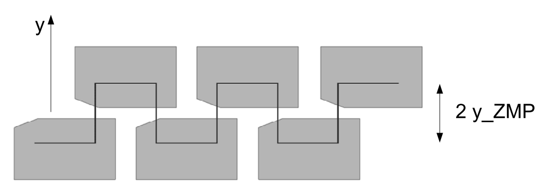


Fig. 3. The desired ZMP position y_{ZMP} (solid line) during a walking motion. y_{ZMP} is always in the middle of the standing foot.

Eq. (1) results in

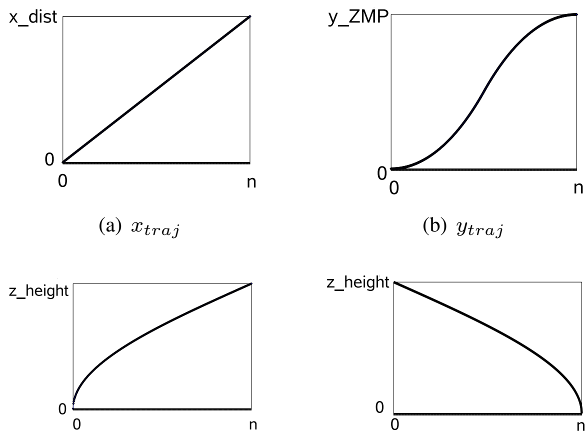
$$\begin{aligned} y(t_i) &= C_1 \cdot e^{\sqrt{\frac{g}{h}} \cdot t_i} + C_2 \cdot e^{-\sqrt{\frac{g}{h}} \cdot t_i} + y_{ZMP} \qquad (2) \\ \text{with } C_1 &= -y_{ZMP} \cdot \left(e^{\sqrt{\frac{g}{h}} \cdot \frac{T}{4}} + e^{-\sqrt{\frac{g}{h}} \cdot \frac{T}{4}} \right)^{-1} \\ C_2 &= C_1 \end{aligned}$$

with T the time for a full stride and t_i the discrete time steps for a full stride with $i = 1, \ldots 4n$

So the trajectory y_{traj} of the swinging leg is calculated with $y(t_i)$ from Eq. (2) by

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

for a discrete time t_i for the first half of a half stride (see Figure 4(b)).



(a) x_{traj} (b) y_{traj}

(c) z_{traj_up} (d) z_{traj_down}

Fig. 4. Trajectories for walking motion for x, y and z.

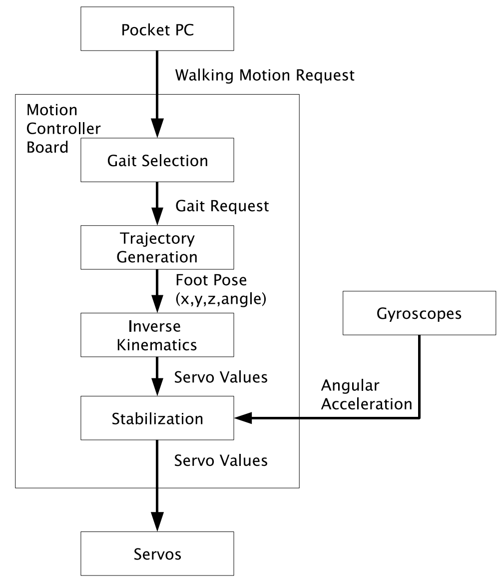


Fig. 5. Structure and dataflow of motion generation. Motion requests made by the robot's behavior control are processed in a series of steps on the motion controller board. After selecting an appropriate gait for the requested motion, the trajectory for the feet is generated using ZMP theory. Using inverse kinematics, the necessary angles for the joints are calculate. To improve walking stability, inertial sensors are used to modify these angles.

The trajectory of the standing leg is calculated in the same way, so that the hip is moving along a S-shaped trajectory and both feet have the same distance in the y axis during a step.

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

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

with x_{dist} the maximum distance of the hip to the standing leg respectively the swinging leg in x direction for a full stride, see Figure 4(a).

The trajectory in direction of z for the swinging leg is calculated differently for upwards and downwards motion of the swinging leg. To reduce the influence of the ground error, the gradient of the curves are high close to the ground, i.e. in the upwards motion at the beginning and in the downwards motion at the end. The trajectories (see Figure 4(c) and 4(d)) are given by

$$\begin{aligned} z_{traj\_up}(t_i) &= \frac{z_{height \cdot c_4}}{\pi}\left(\frac{\pi}{2} - \arcsin\left(1 - \frac{i}{n}\right) - c_3\right) \\ z_{traj\_dw}(t_i) &= z_{traj\_up}(n - t_i) \end{aligned}$$

with z_{height} the maximum desired height in z direction of the foot and $c_3 = 0.75$, $c_4 = 8$ constant values for scaling.

For the standing leg, the z value is defined to be constant.

The angles in the swinging leg and standing leg are calculated based on this trajectories with a fixed angle in z direction in the hip and the condition, that the foot area is parallel to the ground.

The walking motion is stabilized by the gyroscope controller

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

with q respectively q_{new} representing the angles in foot pitch, foot roll, hip pitch, hip roll, waist pitch, shoulder roll and shoulder pitch, k_p and k_d the hand optimized control parameters, ω the angular velocity and t the time.

The improvement of stability achieved by the gyro controller was investigated for three different settings: starting to walk, walking at a speed of 400 mm / sec and during a soccer game.

At the beginning of a walking motion, the robot never falls down with active gyros, but in 65% without an active gyro control the robot falls over backwards.

During the walking motion, the robot walks stable for at least 5 min permanently with activated gyro control. Without gyro control the robot wobbles heavily, thus straining the motors strongly and causing unwanted heating of the motors. Due to the oscillation the robots tends to fall and could not be stabilized in 20 % of the test cases.

During a normal game situation with approaching a ball and kicking it, the robot did fall over during the tests, when the gyro control was not active. This is caused by the numerous motion changes (walk, turn, stand) and the high accelerations in the upper body of the robot.

The interaction of the functional modules of the motion generation are depicted in Figure 5.

b) Fast dynamically walking: Fast dynamically walking is a necessary feature for humanoid robots, especially with the focus on soccer playing.

Model-based optimization approaches need a sufficiently accurate dynamic model of the robot with respect to kinematical and kinetical data like mass distribution and motor properties. The required data are not easy to obtain and, furthermore, effects like gear backlash, elasticity and temperature make it quite difficult to obtain an accurate robot dynamics model. Therefore, a new hardware-in-the-loop optimization method is applied with the physical robot as the evaluator of the objective function for optimization itself.

Five main parameters used for controlling the motion generation where identified by earlier walking experiments. These parameters are the relation of the distances of the front and of the rear leg to the center of mass, the roll angle and height above the ground of the foot during swing phase, and the pitch in the upper body.

Starting with a stable walking motion the applied optimization criterion or objective function for a walking parameter set is the covered walking distance of the robot. The robot starts one optimization cycle with a small stride of 110 mm length and increases by 5 mm each stride during walking up to a maximum of 240 mm length with a constant frequency of approximately 2.85 steps per second.

Except of the noisy objective function evaluation by the real walking robot no further information is given and a non deterministic black-box optimization problem arises. This is solved by a sequential surrogate optimization approach basing on stochastic approximation of the objective function [8]. The physical walking experiments are included as hardware-in-the-loop to determine the objective function value for new generated walking parameter sets during each iteration of the applied optimization approach. Promising parameter sets are the ones, where the robot reached the maximal stride length during the walking experiments. By increasing the frequency at maximal stride length a fast and robust walking motion is found.

c) Multidirectional walking: To achieve a fitting position for kicks to the goal without long-standing positioning in front of the ball, the robot walks multidirectional to the desired pose. The walking motion is generated by amalgamating a forward walking motion with a turning motion.

d) Walking on uneven terrain: Many robots step false and may fall easily when walking on slightly uneven ground like a carpet which is not fixed completely to the ground. In the RoboCup 2006, one of the technical challenges meets this topic by walking on an uneven terrain with height differences of up to 1 cm. A setup of the field can be found in the rule book at [3].

For RoboCup 2005, an adapted foot design was developed [7] respectively Figure 6, left side. Two springs (b) are attached to each foot (a), each one parallel to the longer side of the foot plate. Thus, contact with 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 so that it cannot get stuck with discontinuous ground level. Unevenness of about 10 mm can be walked over without any additional sensors only by tuning the walking parameters. This foot spring design was developed by [13]. It was adapted to the 2006 robot. No redesign of the foot was necessary; the springs can be mounted and still keep the foot size in the rule limitations. For the distance according to the 2006 rules, the robot took about 45 seconds to walk the rough terrain.

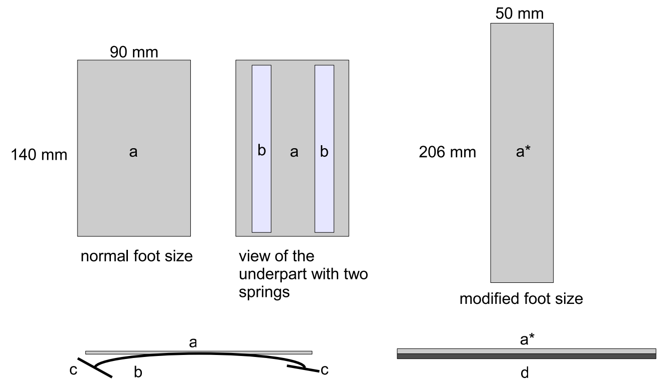


Fig. 6. Two different foot design for walking on a rough terrain. In the left design, two springs (b) are attached on the foot plate (a). On each spring, two moveable plates (c) are mounted to avoid stumbling. In the right design, the foot (a*) is enlarged in the length and shortened in the width. On the underpart, a soft material (d) is added.

Nevertheless, the design approach has been extended in the following way. The base area (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, so that the complete foot area is not enlarged, but even reduced. To absorb the impact of landing a compliant material (d), in this case a sponge, was attached unter the foot. With this modifications and the presented balancing methods, the robot was able to walk over the field within 8 sec (second fastest team: 74 sec). This robust walking motion could be achieved with a minimal set of sensors, consisting of gyroscopes placed in the hip. No foot force sensors or further sophisticated sensors were needed.

B. Special Humanoid Motions

To play soccer with success a large variety of different motions has to be available. This includes kicks for different play situations as well as getting up motions, when the robots falls down, or pre-defined emotional motions (happy when winning, sad when loosing) to make the soccer game more attractive for a non-scientific audience. All the motions have in common that they are developed in advance via teach-in methods.

The adequate kick is selected between 19 available kicking motions, depending on the position of the ball (in front of left or right foot), view angle to the goal, and the validity of the self localization of the robot. These parameters are obtained via a world model given in the control architecture and evaluated in the hierarchical behavior state machine (Sect. V-B).

The getting up motion is initialized by the accelerometer values indicating that the robot has fallen down. 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.

C. Directed viewing

The head motion via two motors 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.

V. Software and Control Architecture

A. Control architecture

The control software is implemented in object oriented C++ and consists of several modules for the different tasks (see Figure 7) [6].

Based on the images of 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 goalie). The percepts are timestamped and used for modeling of the environment. The control software contains a Kalman filter for ball modeling and a Markov localization with particle filtering [5] for self localization.

Robots share their world model with the other team members via UDP broadcast to achieve a fast communication. This way, the robots decisions can be based on information which would normally not be available.

To obtain information about the current state of the game, the robots receive UDP broadcasts sent from an external computer running a game controller. This game controller is a modified version of the one used in the RoboCup 4-legged league. The transmitted datagram contains the current game phase, team colors, playing directions and the score.

B. Behavior

The behavior 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) [15]. The language specifies hierarchies of finite state machines (FSM).

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.

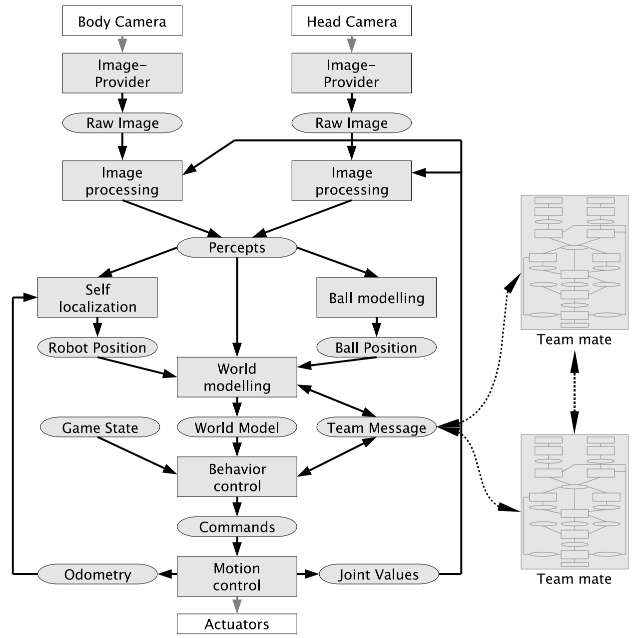


Fig. 7. Overview of modules (rectangles) and exchanged messages (ellipses) of the control software. White blocks are sensors or actuators, gray blocks are modules executed on the Pocket PC.

The discrete state transitions are well suited when realizing high-level long-term behavior decisions or low-level discrete decisions like performing a special action e.g. a kick. But they are not really suitable when trying to achieve continuous behavior like walking to a position while avoiding obstacles. 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.

VI. Results

The following results were all shown at the RoboCup2006.

A. Demo footrace

Bruno was the only humanoid robot participating in demo races against several four-legged Aibo robots at RoboCup 2006. The humanoid robot was able to keep up with the highly optimized walking of the four-legged robots (see Figure 8). With an average speed of over 40 cm/s the HR18 reached a fifth place among the seven participants. In another demo race it outran the two finalists of the footrace competition from the taller teen-size humanoid class.

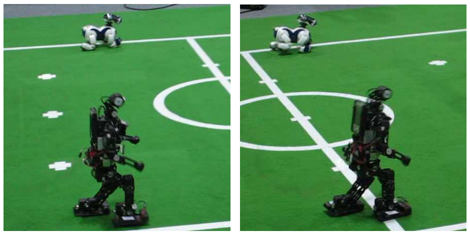


Fig. 8. The fastest humanoid robot at the RoboCup2006 was able to keep up with the optimized walking speed of an Aibo.

B. Backheel kick

In a game during 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 accurate position and orientation. Therefore the behavior decided to kick the ball with a very specific backheel kicking motion (as illustrated in Fig. 9) and scored a 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.

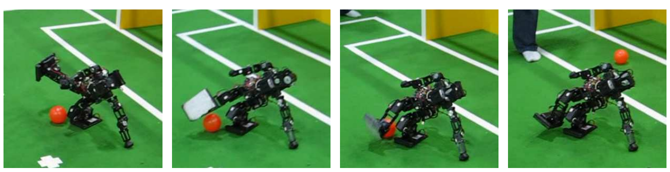


Fig. 9. The HR18 scoring a goal by performing a backheel kick.

C. Cooperative team behavior

Besides the versatile motions the robots also showed high-level team behavior. The behavior used the communicated information of the teammate to decide the dynamic role during game. Similar methods have been applied by the German Team in the four-legged league [19]. In Figure 10 both robots approached the ball. Based on the communicated distance 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 obstruction of its own teammate.

Fig. 10. 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.

VII. Conclusions and outlook

In this paper the development of the 55cm tall, autonomous humanoid robot Bruno has been described. During RoboCup 2006 Bruno has demonstrated a variety of high-quality motions including the fastest forward walking and the first-ever backheel kick of a humanoid robot. Control of individual robot and team behavior for autonomous robot soccer playing capabilities was achieved 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 3 teams at RoboCup 2006 which used directed and not omni- or circumferential vision for perception and localization.

Ongoing work aims towards improved capabilities for vision including obstacle and opponent recognition and higher levels of intelligence during autonomous soccer games.

VIII. Acknowledgment

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