See, walk, and kick: Humanoid robots start to play soccer

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***Abstract*— Robotic soccer superseded chess as a challenge problem and benchmark for artificial intelligence research and poses many challenges for robotics. The international RoboCup championships grew to the most important robotic competition worldwide. This paper describes the mechanical and electrical design of the robots that we constructed for RoboCup 2006, which took place in Bremen, Germany. The paper also covers the software used for perception, behavior control, communication, and simulation. Our robots performed well. The KidSize robots won the Penalty Kick competition and came in second the overall Best Humanoid ranking, next only to the titleholder, Team Osaka.**

I. Introduction

What drives thousands of researchers worldwide to devote their creativity and energy to make robots bring a ball into a goal? The answer lies not only in the fascination of the soccer game, but rather in the quest to advance the fields of artificial intelligence research and robotics.

AI researchers started to investigate games early-on. Already in the 1950th, Simon predicted that computers would be able to win against the human world champion within ten years [13]. Playing chess was viewed as epitome of intelligence. The dominant view at that time was that human intelligence could be simulated by manipulating symbols. While the world champion in chess was defeated by a machine in 1997 [10], human intelligence is still far from being understood.

The basis for intelligent action is the perception of the world. Already this seemingly easy task frequently exceeds the capabilities of current computer systems. Perceptual processes, which interpret the flood of stimuli that stream into our senses and make it accessible for behavior control, are mostly unconscious. Hence, we are not aware of the difficulties involved. The performance of our perceptual system becomes clear only when trying to solve the same task with machines. This applies to behavior control as well. Human locomotion, for example, does not seem to be problematic. That walking and running on two legs is not an easy task becomes clear only when one tries to implement it on a real robot.

Based on these observations, a view on intelligence has established itself over the last two decades that does not rely on manipulating symbols, but emphasizes the interaction of an agent with its environment [5], [11]. The term embodiment stresses the importance of having a body as the physical basis for intelligence. Situatedness of an agent in a rich environment enables feedback from its actions to its sensory signals. The complexity of the interaction is increased significantly when the environment does not only contain passive objects, but other agents as well.

A. RoboCup Competitions

Motivated by the success in the chess domain, the RoboCup Federation organizes since 1997 international robotic soccer competitions. Similar competitions are organized by the competing FIRA. The long-term goal of the RoboCup Federation is to develop by the year 2050 a team of humanoid soccer robots that wins against the FIFA world champion [9]. The soccer game was selected for the competitions, because, as opposed to chess, multiple players of one team must cooperate in a dynamic environment. Sensory signals must be interpreted in real-time and must be transformed into appropriate actions. The soccer competitions do not test isolated components, but two systems compete with each other. The number of goals scored is an objective performance measure that allows comparing systems that implement a large variety of approaches to perception, behavior control, and robot construction. The presence of opponent teams, which continuously improve their system, makes the problem harder every year. Such a challenge problem focuses the effort of many research groups worldwide and facilitates the exchange of ideas.

The RoboCup championships grew to the most important robotic competition worldwide. In the last RoboCup, which took place in June 2006 in Bremen, Germany, 440 teams from 36 countries competed. The total number of participants was more than 2.600. In addition to the soccer competitions, since 2001, competitions for the search of victims of natural disasters and the coordination of rescue forces are held (RoboCupRescue). Furthermore, there are competitions for young researchers (RoboCupJunior).

B. RoboCupSoccer

The soccer competitions at RoboCup are held in five leagues. Since the beginning, there is a league for simulated agents, a league for small wheeled robots which are observed by cameras above the field (SmallSize), and a league for larger wheeled robots where external sensors are not permitted (MiddleSize). A league for the Sony Aibo dogs was added in 1999 (Four-legged) and a league for humanoid robots was established in 2002.

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Fig. 1. Some of the RoboCup 2006 Humanoid League robots.

Different research issues are addressed in the different leagues. In the simulation league, team play and learning are most advanced. In the wheeled robot leagues, the robot construction (omnidirectional drives, ball manipulation devices), the perception of the situation on the field (omnidirectional vision systems, distance sensors), and the implementation of basic soccer skills (approaching, controlling, dribbling, and passing the ball) are still in the center of the activities. Because the robot hardware is fixed in the Four-legged League, the participating teams focus on perception and behavior control. Here, the control of the 18 degrees of freedom (DOF) poses considerable challenges.

As the performance of the robots increases, the competition rules are made more demanding by decreasing the deviations from the FIFA laws. This permanently increases the complexity of the problem. It can also be observed that solutions like team play, which have been developed in leagues abstracting from real-world problems, are adopted in hardware leagues, as the basic problems of robot construction, perception, locomotion, and ball manipulation are solved better.

C. Humanoid Soccer Robots

In the Humanoid League, robots with a human-like body plan compete with each other. The robots must have two legs, two arms, a head, and a trunk. Size restrictions make sure that the center of mass of the robots is not too low, that the feet are not too large, and so on. The robots are grouped in two size classes: KidSize (¡60cm) and TeenSize (¿65cm). The humanoid robots must be able to walk on two legs. While in the first years of the league, it was allowed to remotely control the robots and to use a power cable, since 2004, the robots must be fully autonomous. The robots may communicate with each other via a wireless network, but help from outside the field is not permitted, neither by humans nor by computers.

Because the construction and the control of humanoid robots is significantly more complex than that of wheeled robots, initially, there were only preliminary competitions held, but no soccer games played, in the Humanoid League. The robots had to footrace around a pole and faced each other in penalty kicks. Since 2005, soccer games take place.

The Humanoid League rules [1] have been derived from the FIFA laws. Some simplifications apply, however. For example, the offside rule is not observed. Key objects are color-coded in order to simplify the perception of the game situation. The playing field is green with white lines, the goals are painted blue and yellow, the ball is orange, and the robots are mostly black. The two teams are marked with magenta and cyan patches, respectively.

The remainder of this paper is organized as follows. In the next section, we describe the mechanical design of the robots. Sec. III details the robot electronics. The perception of the internal robot state and the situation on the field is covered in Sec. IV. Sections V and VI explain the generation of soccer behaviors in a hierarchy of agents and time-scales and the infrastructure needed to support a team of soccer playing robots, respectively.

II. Mechanical Design

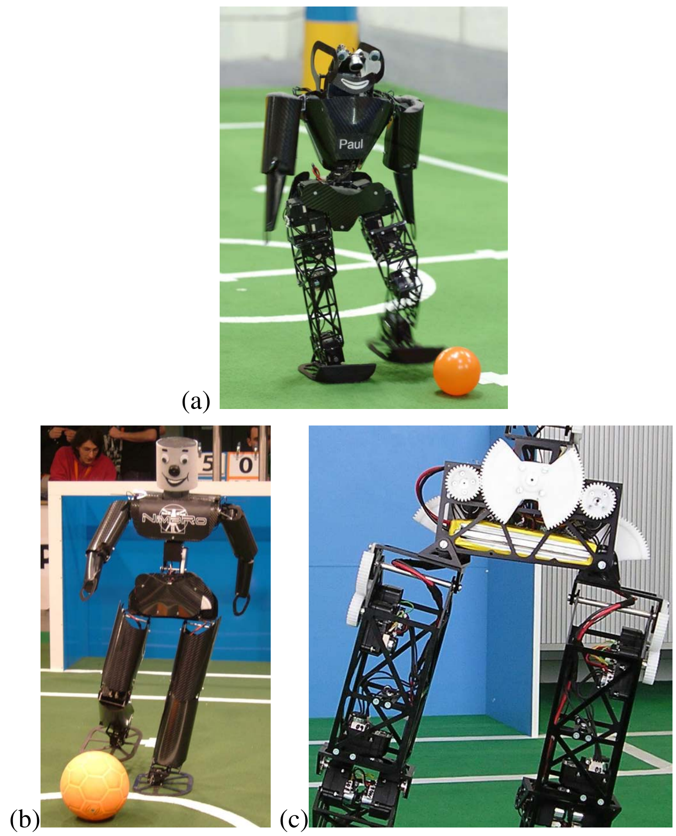


Fig. 2. NimbRo 2006 robots: (a) KidSize robot Paul, (b) TeenSize robot Robotinho, (c) close-up of Robotinho's mechanics.

Fig. 2 shows Paul, one of our 2006 KidSize robots, and Robotinho, our 2006 TeenSize robot. Their predecessors Jupp, Sepp, and Max [4] came in second in the Best Humanoid ranking at RoboCup 2005. As can be seen, the robots have human-like proportions. Their mechanical design focused simplicity, robustness, and weight reduction.

The KidSize robot has a height of 60cm and a weight of only 2.9kg, including batteries. It is driven by 24 Dynamixel actuators: 8 per leg, 3 in each arm, and two in the trunk. For the leg and the trunk joints, we use the DX-117 actuators (66g, 37kg·cm at 16V). Three orthogonal axes constitute the

3DOF hip joint. For the hip pitch and roll axes, we use two of these actuators in parallel. The actuators are coupled in a master-slave configuration. This doubles the torque and lowers operating temperatures. The master-slave pair of actuators has the same interface as the single actuators used for all other joints. Two orthogonal servos form the 2DOF ankle joint. One servo drives the knee joint. The trunk joints are in the pitch and yaw axes. The arms do not need to be as strong. They are powered by DX-113 actuators (10.2kg·cm, 58g). Two orthogonal servos constitute the shoulder joint and one servo drives the elbow joint.

The TeenSize robot Robotinho is 100cm tall and has a total weight of about 5kg. Its 21 DOF are driven by a total of 33 DX-117 actuators. The additional joint is the roll axis in the trunk. All joints in the legs and the trunk, except for the yaw axes, are driven by two parallel actuators. The hip and trunk yaw axes are reinforced by external 2:1 spur gears. The hip and trunk roll axes are reduced by 3:1, resulting in a holding torque of 222kg·cm at 16V.

The skeleton of the robots is constructed from aluminum extrusions with rectangular tube cross section. In order to reduce weight, we removed all material not necessary for stability. The feet and the forearms are made from sheets of carbon composite material. The elasticity of the feet and the carpet, the robots walk on, helps to maintain non-degenerate foot-ground contact, even when the supporting foot is not parallel to the ground. Robotinho's head is made of lightweight foam. The upper part of the KidSize robot and the entire body of the TeenSize robot is protected by a layer of foam and an outer shell of thin carbon composite material.

III. Electronics

Our soccer robots are fully autonomous. They are powered by high-current Lithium-polymer rechargeable batteries, which are located in their hip. Four Kokam 910mAh cells are used for the KidSize robot. Robotinho has four Kokam 3200mAh cells. The batteries last for about 25 minutes of operation.

The Dynamixel actuators have a RS-485 differential half-duplex interface. Each robot is equipped with a CardS12 microcontroller board, which manages the detailed communication with all Dynamixels. These boards feature the Motorola MC9S12D64 chip, a 16-bit controller belonging to the popular HCS12 family. We clock it with 32MHz. It has 4kB RAM, 64kB flash, two serial interfaces, CAN bus, 8 timers, 8 PWM channels, and 16 A/D converters.

The Dynamixel actuators have a flexible interface. Not only target positions are sent to the actuators, but also parameters of the control loop, such as the compliance. In the opposite direction, the current positions, speeds, loads, temperatures, and voltages are read back. In addition to these joint sensors, each robot is equipped with an attitude sensor, located in the trunk. It consists of a dual-axis accelerometer (ADXL203, $\pm$1.5g) and two gyroscopes (ADXRS 300, $\pm$300 °/s). The four analog sensor signals are digitized with A/D converters of the HCS12 and are preprocessed by the microcontroller. The microcontroller communicates with the Dynamixels via RS-485 at 1MBaud and with a main computer via a RS-232 serial line at 115KBaud. Every 12ms, target positions and compliances for the actuators are sent from the main computer to the HCS12 board, which distributes them to the actuators. The microcontroller sends the preprocessed sensor readings back. This allows keeping track of the robot's state in the main computer.

We use a Pocket PC as main computer, which is located in upper part of the robots. The FSC Pocket Loox 720 has a weight of only 170g, including the battery. It features a 520MHz XScale processor PXA-272, 128MB RAM, 64MB flash memory, a touch-sensitive display with VGA resolution, Bluetooth, wireless LAN, a RS-232 serial interface, and an integrated 1.3 MPixel camera. This computer runs behavior control, computer vision, and wireless communication. It is equipped with a Lifeview FlyCam CF 1.3M that has been fitted to an ultra-wide-angle lens. Robotinho's FlyCam lens also serves as nose. It looks in forward direction. For the KidSize robots, we took the integrated camera out of the Pocket PC and connected it via an extension cable. This camera uses the QuickCapture feature of the XScale chipset. 640$\times$480 images can be captured at 15fps using DMA. The camera is fitted to a wide-angle converter. Located above the Pocket PC, it looks in forward direction. The FlyCam is looking in backward direction in the KidSize robots.

IV. Perception

Our robots need information about themselves and the situation on the soccer field to act successfully. In this section, we detail proprioception, the visual perception of key objects and self-localization.

A. Proprioception

On the Pocket PC, the readings of accelerometers and gyros are fused to estimate the robot's tilt in roll and pitch direction. For each axis, the gyro bias is calibrated, assuming that over intervals of 2.4s the integrated bias-corrected gyro rates equal the difference between the tilts estimated from the accelerometers. Here we assume that, in the long run, the accelerometers measure the decomposition of the gravity vector. Combining the low-frequency components of the tilt estimated from accelerometers with the integrated bias-corrected gyro rates yields an estimate of the robot's attitude that is insensitive to short linear accelerations. As described above, joint angles, speeds, loads, temperatures, and voltages are also available. The temperatures and voltages are used to notify the user in case of overheating or low batteries.

B. Visual Object Detection

The only source of information about the environment of our robots is their camera. The wide field of view of the camera(s) allows them to see at the same time their own feet and objects above the horizon. Figure 3 shows on the left two images captured from the perspective of a robot on the field.

Our computer vision software detects the ball, the goals, the corner poles, the field lines, and other players based on their

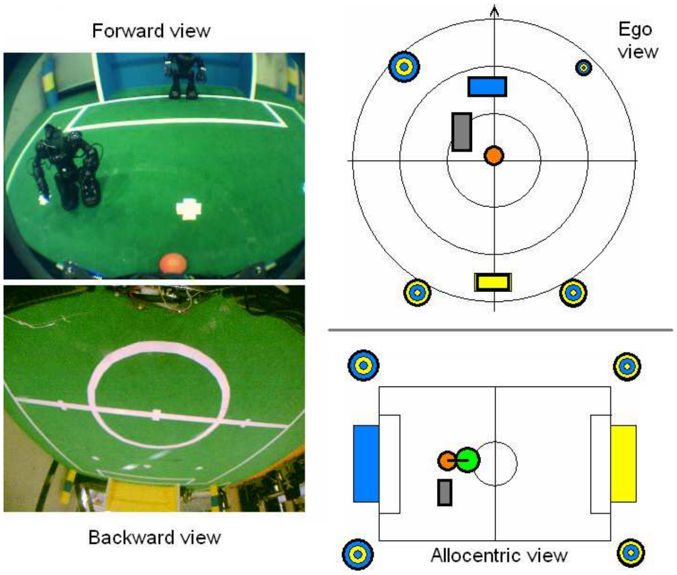


Fig. 3. Left: Images of the two cameras mounted on a KidSize robot. Upper right: Egocentric coordinates of key objects (ball, goals, corner poles, obstacle) detected in the image. Lower right: Localization of the robot, the ball, and the obstacle on the soccer field.

color. The FlyCam captures RGB images with a resolution of 320×240 pixels. The images are converted into the YUV color space to decrease the influence of different lighting conditions. The forward camera directly delivers YUV 4:2:2 images. Using a look-up table, the colors of individual pixels are classified into color-classes that are described by ellipsoids in the UV-plane. We correct for the average brightness and for the darkening of the lens towards the periphery. In a multistage process we discard insignificant colored pixels and detect colored objects. We estimate their coordinates in an egocentric frame (distance to the robot and angle to its orientation), based on the inverted projective function of the camera. We correct first for the lens distortion and invert next the affine projection from the ground plane to the camera plane. The estimated egocentric coordinates of the key objects are illustrated in the upper right part of Fig. 3. Here, the objects detected by both cameras are fused, based on their confidence.

C. Self-Localization

The relative coordinates suffice for many relative behaviors, like positioning behind the ball while facing the goal. To implement team behaviors, such as kick-off, we need the robot coordinates in an allocentric frame ((x, y)-position on the field and orientation θ). If both goals are visible, self-localization can be done easily by triangulation, as shown in the lower-right corner of Fig. 3. The corner poles can be used in a similar way if one of the goals is outside the field-of-view.

In addition to the already mentioned detected objects, the field lines are used for self-localization. This is necessary for the TeenSize robot, which has only one directed camera.

Figure 4 illustrates the detection of the center circle and the field lines. We use four oriented line detectors to detect points belonging to field lines. The detectors make sure that green is present on both sides of the line. The detected line points are aggregated locally to larger line segments and transformed into an egocentric Cartesian frame.

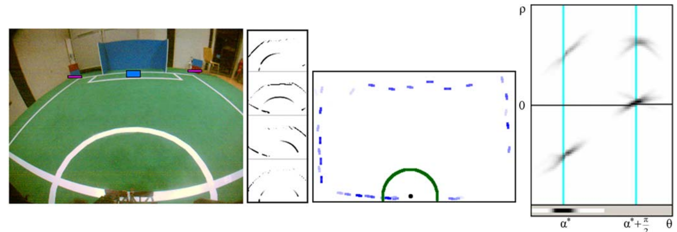


Fig. 4. Detection of field lines (left to right): image captured by a walking robot, responses of four orientated line detectors, oriented line segments with removed center circle, Hough space with major orientation α^* and main lines.

Next, we locate the center circle [6]. The individual line segments vote for positions at a distance of the radius of the center circle, orthogonal to the orientation of the segment. By determining the largest cluster of points, we find and eliminate the segments corresponding to the center circle. The remaining line segments are transformed into the Hough space [8]. Since we have already estimated the orientation of the line segments, we only have to vote for a small subset of orientation bins. Utilizing the property that the field lies are orthogonal, we determine the main orientation α^* (modulo $\frac{\pi}{2}$) and find for each corresponding orientation the two most significant lines.

The observations of the field lines, the center circle, the goals, and the corner poles are integrated in a particle filter [7] with the motion commands sent to the robot. We compare the observed positions of landmarks with the expected positions of the landmarks that should be visible from the particle poses. For the field lines, we use not only the Hough parameters (θ, ρ) to assess similarity, but also two parameters that describe line position and length. We also apply a motion model that moves the particles according to the motion commands sent to the robot. The particle filter yields an estimate of the robots pose (x, y, θ) on the field. More details can be found in [16].

V. Behavior Control

We control the robots using a framework that supports a hierarchy of reactive behaviors [3]. This framework allows for structured behavior engineering. Multiple layers that run on different time scales contain behaviors of different complexity. The framework forces the behavior engineers to define abstract sensors that are aggregated from faster, more basic sensors. One example for such an abstract sensor is the robot's attitude that is computed from the readings of accelerometers and gyros. Abstract actuators allow higher-level behaviors to configure lower layers in order to eventually influence the state of the world. One such abstract actuator is the desired walking direction, which configures the gait engine, described below, implemented in the lower control layers.

The framework also supports an agent hierarchy. For our soccer robots, we use four levels of this hierarchy: individual joint – body part – entire robot – team. This structure restricts interactions between the system variables and thus reduces the complexity of behavior engineering.

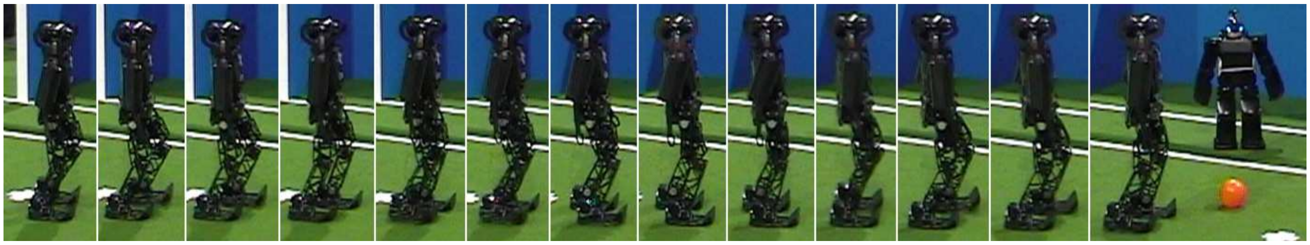


Fig. 5. Forward walking while approaching the ball.

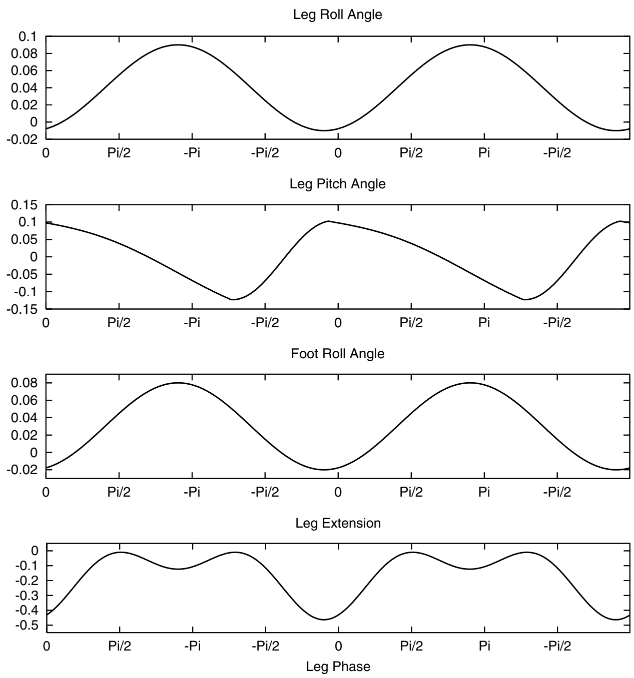


Fig. 6. Trajectories for forward walking of KidSize robot.

The lowest level of this hierarchy, the control loop within the Dynamixel actuators, has been implemented by Robotis. It runs at a high frequency. We monitor targets, actual positions, speeds, and loads. At the next layer, we generate target positions for the individual joints of a body part at a rate of 83.3Hz. We make sure that the joint angles vary smoothly. To abstract from the individual joints, we implemented here, for example, an interface that allows to change leg extension, leg angle, and foot angle.

On the next higher level, we use this leg interface to implement omnidirectional walking. Shifting the weight from one leg to the other, shortening of the leg not needed for support, and leg motion in walking direction are the key ingredients of this gait. In contrast to the low-frequency gait of our 2005 robots [2], we were able to increase the step frequency significantly to 2.44Hz for Robotinho and 3.45Hz for the KidSize robots.

Fig. 6 shows the trajectories generated for forward walking. Note that the leg is not only shortening during swing, but also in the middle of the stance phase. The resulting gait is depicted in Fig. 5.

Walking to the side and rotating on the spot is generated in a similar way. The three basic walking directions can be smoothly combined. The robots are able to walk in every direction and to change their heading direction at the same time. The gait target vector (v_x, v_y, v_θ) can be changed continuously while the robot is walking. This makes it possible to correct for deviations in the actual walking direction and to account for changes in the environment by using visual feedback. When using this flexible gait, the maximal forward walking speed of the robots is approx. 25cm/s, but they walk slower in the vicinity of obstacles and the ball. We used omnidirectional walking to implement basic soccer skills, like approaching the ball and dribbling. In addition to walking, we implemented kicking, obstacle avoidance, and defensive behaviors. Fig. 7 shows different phases of a kick.

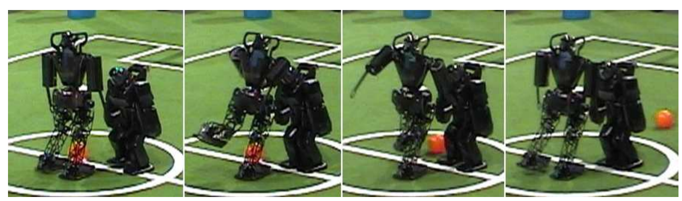


Fig. 7. Kicking the ball.

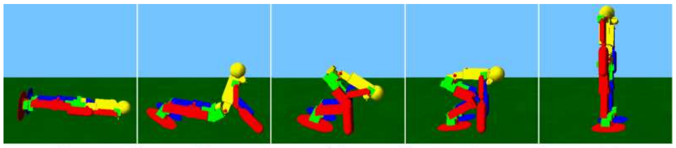
Since in soccer games physical contact between the robots is unavoidable, the walking patterns are disturbed and the robots might fall. Hence, they must be able to detect the fall, to recognize their posture on the ground, and to get back into an upright posture. After falling, the robot's center of mass (COM) projection to the ground is outside the convex hull spanned by the foot-contact points. Additional support points, like knees, elbows, and hands, must be used in order to move the COM back inside the foot polygon.

Using their attitude sensors, the robots detect a fall, classify the prone or supine posture and trigger the corresponding getting-up sequence. We designed the getting-up sequences in the simulator using sinusoidal trajectories [15]. Fig. 8 illustrates the four phases of getting up from the prone posture and Fig. 9 illustrates getting up from the supine posture. The getting-up sequences work very reliably. Under normal circumstances, i.e. appropriate battery voltage, the routines worked with 100 successes in 100 tests.

VI. Infrastructure

In addition to the robots themselves, some infrastructure components are needed to support a team of soccer playing robots. They include wireless communication and a simulator.

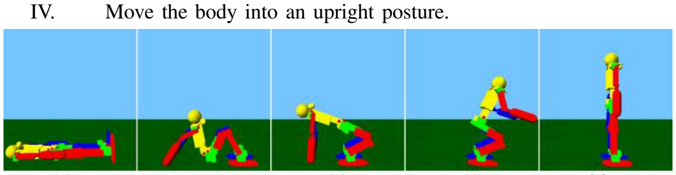
I. Lift the trunk and bring the forearms under the shoulders.
II. Move the COM projection as close as possible to the leading edges of the feet by bending in the spine, the hip pitch and the knee joints.
III. Straighten the arms to let the robot tip over the leading edges of the feet.
IV. Bring the body into an upright posture.



(a) → I → (b) → II → (c) → III → (d) → IV → (e)

Fig. 8. Standing up from the prone posture.

I. Move the upper body into a sit-up posture and move the arms into a supporting position behind the back.
II. Move into a bridge-like position using the arms as support.
III. Move the COM over the feet by swinging the upper body to the front.
IV. Move the body into an upright posture.



(a) → I → (b) → II → (c) → III → (d) → IV → (e)

Fig. 9. Standing up from the supine posture.

A. Wireless Communication

The Pocket PCs of our robots are equipped with wireless network adapters. We use the wireless communication to transmit via UDP debug information to an external computer, where it is logged and visualized. This allows the behavior engineers to keep track of the perceptions and the chosen actions. The wireless network is also used for transmitting the game state (kickoff, penalty ...) from the external PC to the robots. The robots communicate with each other to share perceptions. E. g., if one robot does not see the ball, it might use the ball observation of its teammate to find the ball again.

The importance of team behaviors is still low in the Humanoid League, as only 2 players per team have competed so far. In Bremen 2006, most teams assigned one player to keep the goal clear and used the other player as field player. For the play with two field players, we implement some role negotiation between the players. As soon as one of our players has control of the ball, the other player goes to a defensive position between the ball and the own goal.

B. Simulation

In order to be able to design behaviors without access to the real hardware, we implemented a physics-based simulation for the robots. This simulation is based on the Open Dynamics Engine [14]. It was very helpful for the design of getting-up behaviors, goalie behaviors, and team behaviors. The simulator is also used to develop learning algorithms, which are then applied to the real robots.

VII. Results

Our robots performed well at RoboCup 2006, where 21 teams from 11 countries competed in the Humanoid League. In the technical challenge, our KidSize robot Gerd was one of the two robots able to walk across the rough terrain (see Fig. 10). Our KidSize robots also scored in the passing challenge.

In the KidSize Penalty Kick final (Fig. 11(a)) our robots won 8:7 against Team Osaka [17]. Our KidSize robots also reached the final in the 2 vs. 2 soccer games against Team Osaka. They scored an early lead of 4:0 against the Japanese robots (Fig. 11(b)). After a debatable goal directly from kick-off the score at halftime was 4:1. Due to hardware problems of our robots, Team Osaka was able to reach a draw of 4:4 after regular playing time. As we already had taken the available two substitutions, we needed to continue playing with impaired robots in the extra time. The final score was 9:5 for Team Osaka. Our TeenSize robot Robotinho also reached the final in the Penalty Kick competition (Fig. 11(c)). Team Osaka won this match 3:1. In the overall Best Humanoid ranking, our KidSize robots came in second, next only to the titleholder, Team Osaka. Videos showing the performance of our robots at RoboCup 2006 can be found at http://www.NimbRo.net.

VIII. Conclusions

This paper described the mechanical and electrical design of our robots, which successfully took part as team NimbRo at the RoboCup 2006 competitions. We detailed the software used for perception, behavior control, and communication.

Playing soccer with humanoid robots is a complex task, and the development has only started. So far, there has been significant progress in the Humanoid League, which moved in its few years from remotely controlled robots to soccer games with fully autonomous humanoids. Indeed, the Humanoid League is currently the most dynamic RoboCupSoccer league. We expect to see the rapid progress continue as more teams join the league. Many research issues, however, must be resolved before the humanoid robots reach the level of

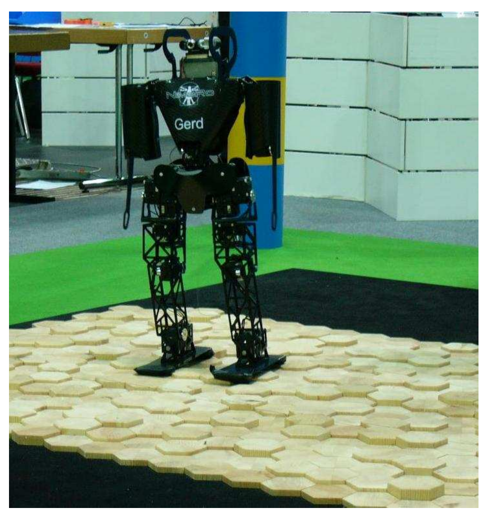
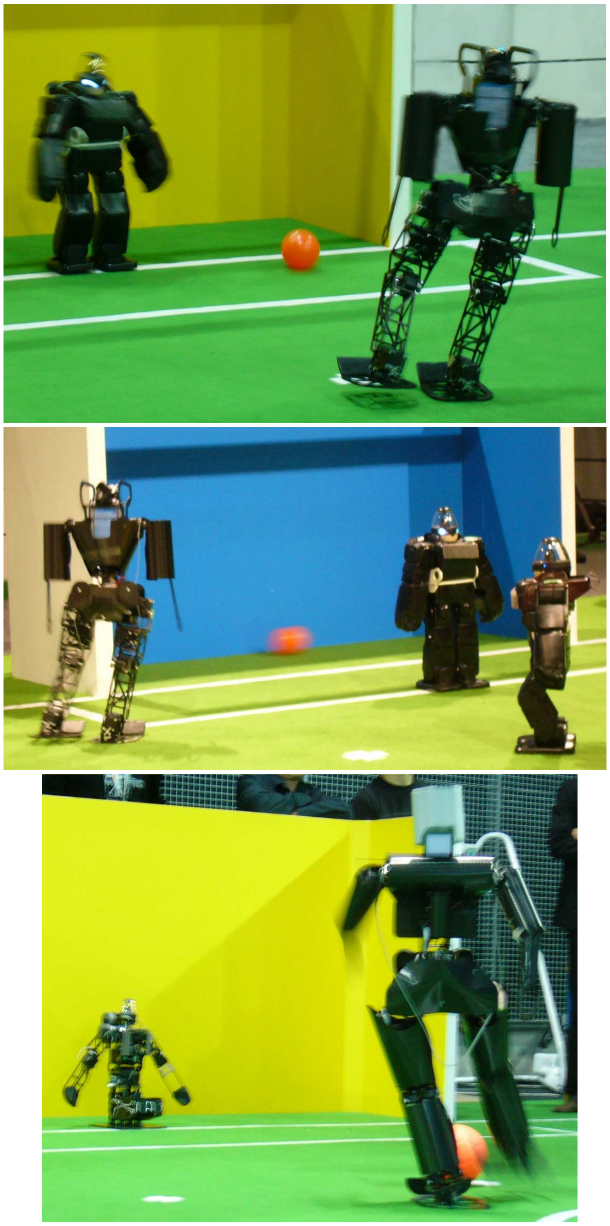


Fig. 10. RoboCup 2006: KidSize robot Gerd walking over rough terrain.



(a)
(b)
(c)

Fig. 11. RoboCup 2006: (a) KidSize Penalty Kick final NimbRo vs. Team Osaka. (b) 2 vs. 2 Soccer final NimbRo vs. Team Osaka. (c) TeenSize Penalty Kick final NimbRo vs. Team Osaka.

play shown in other RoboCupSoccer leagues. For example, the humanoid robots must maintain their balance, even when disturbed. Currently, we are working on postural reflexes, which should minimize the number of falls [12].

In the next years, the speed of walking must be increased significantly. We work on automatic gait optimization to increase both speed and stability. At higher speeds, running will become necessary. We recently started to explore this direction. The visual perception of the soccer world must become more robust against changes in lighting and other interferences. We continuously improve our computer vision software to make it more reliable.

Among the biggest challenges when designing a team of soccer playing robots is the integration of subsystems. While it is not that hard to develop a vision system or to implement walking, it is not easy to operate these components simultaneously within a humanoid robot. The weight and power consumption of the components plays a role that should not be underestimated. High reliability of all parts, as well as the handling of exceptions are indispensable in order to survive a game without breakdowns. As the performance of the system is not determined by the strongest component, but by the weakest link in the chain, this component deserves our attention in future research.

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