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# Playing Soccer with Humanoid Robots

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**As step towards the long-term goal of winning against the FIFA world champion, the RoboCup Federation added in 2002 a league for humanoid robots to its annual soccer competitions. Now, the young Humanoid League raised the bar again. After preliminary competitions, for the first time, soccer games with humanoid robots were played in 2005.**
**This article describes the technology of the humanoid soccer robots, explains the rules of the league, and gives an outlook to the research issues that must be addressed in the future.**

## 1 Introduction

Humanoid robots, robots with an anthropomorphic body plan and human-like senses, enjoy increasing popularity as object of research, especially in Japan. This is motivated by the vision to create a new kind of tool: robots that work in close cooperation with humans in the same environment that we designed to suit our needs. Some of the skills needed for these robots are developed in the soccer domain.

Spurred by the rapid progress in the wheeled and four-legged soccer leagues, the RoboCup Federation added in 2002 a league for humanoid robots to the competitions. This is one step towards the long-term goal of winning against the FIFA world champion. The competing FIRA established a humanoid league (HuroSot) as well.

While the Humanoid League builds on techniques developed for wheeled and four-legged soccer robots, some research issues arise that are specific for humanoid soccer robots. Among the research challenges addressed in this league is maintaining dynamic stability of the robots while walking, running, and kicking. Another research issue is the coordination of bipedal locomotion and perception. As robots go to the floor intentionally as goal keeper or without intention, e.g. due to physical contact with other players, getting up from the ground is also important in order to continue to play.

This article is structured as follows. The next section covers the history of the Humanoid League and explains its rules. Section 3 describes the robot hardware, and Section 4 details perception, control, and communication software. The article concludes with a summary of the results of the 2005 competition and an outlook to future research challenges.

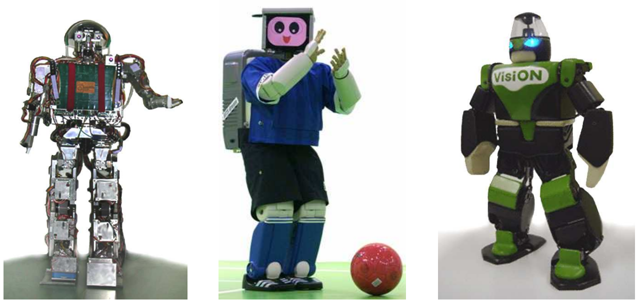
## 2 Humanoid League

Four international competitions took place in the RoboCup Humanoid League so far. Because the complex humanoid robots were not ready to play real soccer games in the first three competitions, the robots had to demonstrate their capabilities by solving a number of subtasks.

In the Humanoid Walk, they had to footrace towards a pole, to walk around it, and to come back to the start. Scoring was based on walking speed and stability. In the penalty kick competition, the robots faced each other. While one robot tried to score a goal, the other defended. In the freestyle competition, the robots had five minutes to show a performance to a jury. Each year, there was also a new technical challenge. In 2004, it consisted of an obstacle walk, a passing task, and balancing across a sloped ramp.

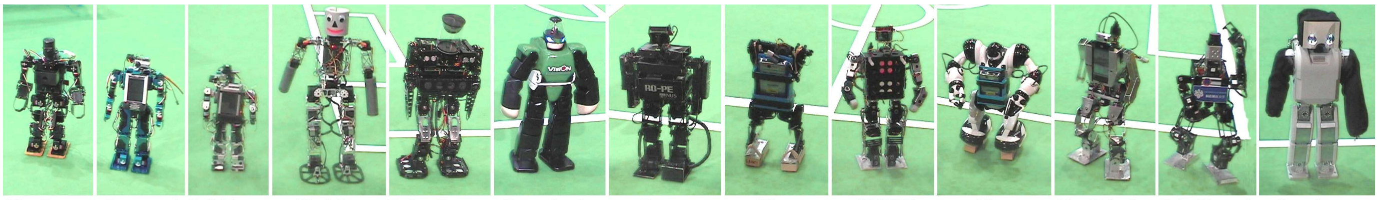
The RoboCup Humanoid League competition rules [15] require that the robots have a human-like body plan. They must consist of a trunk, two legs, two arms, and a head. The only allowed mode of locomotion is bipedal walking. Size restrictions make sure that the center of mass of the robots is not too low, that the feet are not too large, and so on. As robots of very different sizes cannot compete directly, the robots were grouped into three size classes: H40 (<44cm), H80 (<80cm), and H120 (<180cm). Initially, external power supply, external computing power, remote control, and the use of commercial robot platforms were discouraged by performance factors. These factors were applied to trial times and goal counts. Now, the robots must be fully autonomous. They may communicate with each other via a wireless network, but help from outside the field is not permitted, neither by humans nor by computers.

The results of the individual competitions are aggregated to a Best Humanoid ranking. So far, all winning teams in the Humanoid League have come from Japan. Fig. 1 shows the winning robots of the first three competitions. In 2002, the Nagara robot (83cm, 15kg, 28DOF) was the overall winner. It was constructed by the industries association of the Gifu prefecture. A Honda Asimo prototype (125cm, 50kg, 26DOF) of team HITS Firstep [13] won in 2003. It had an expressive face and could walk at about 42cm/s. By walking through it, Asimo kicked the ball against a human goalkeeper. Team Osaka won the 2004



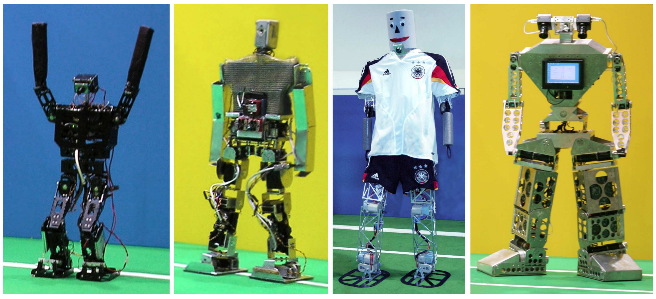
2002 Nagara 2003 HITS Firstep 2004 VisiON

Figure 1: Winners of the RoboCup Humanoid League.



Hits Dream Darmstadt Dribblers NimbRo Robo-Erectus Team Osaka Rope Hiro KMUTT Hiro Sharif Cedra Toin Phoenix Senchans

Figure 2: Some of the robots that competed at RoboCup 2005 in the Humanoid League KidSize class.



Robo-Erectus Aria Fritz of NimbRo GuRoo

Figure 3: Some of the robots that competed at RoboCup 2005 in the Humanoid League MidSize class.

competition with the robot VisiON (39cm, 2.4kg, 23DOF) [19]. It was constructed by a consortium of companies (Vstone, Systec Akazawa, Robo Garage), the University of Osaka, and the ATR research institute. The robot used an omnidirectional camera as head. As a goalie it turned one shoulder towards the ball in order to jump quickly to the ground when the ball came close. Afterwards, it could get up by itself. Another highlight of the 2004 competition was the passing demonstration shown by two Hoap robots of team Senchans.

The 2005 competition took place in Osaka, Japan. Here, the size classes were reduced to two: KidSize (<60cm) and MidSize (<180cm). Figures 2 and 3 show some of the participating robots. A total of 20 teams from 9 countries competed in the Humanoid League, including two German teams: Darmstadt Dribblers [10] and NimbRo [4]. Most participating robots were constructed by the research groups, but also some commercially available robots participated.

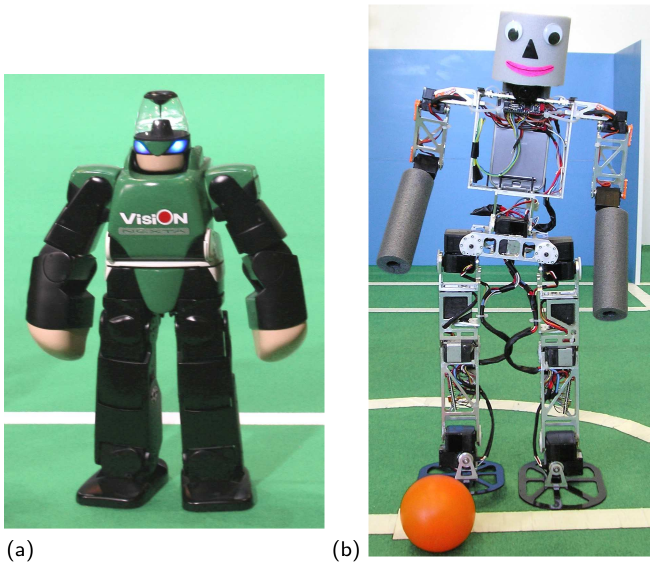
The presumably most expensive robot was used by the team Senchans [7]. It is the new Hoap-3 (60cm, 8.8kg, 28DOF) [11], which Fujitsu hopes to sell hundred times to research institutes for a price of approx. EUR 50,000. Some teams used the construction kit Kondo KHR-1 [14] (34cm, 1.2kg, 17DOF), which is sold for approx. EUR 1,100. The team Hiro [1] used modified RoboSapiens (34cm, 2.1kg, 7DOF) in the competitions, which only cost approx. EUR 60, because they were developed for the toy market [20].

2005 was the first year that soccer games took place. At the German Open in April 2005, two teams of autonomous RoboSapien robots (Brainstormers und NimbRo) showed demonstration games with up to four robots per team [5]. In Osaka, 2 vs. 2 soccer games were played in the KidSize class. The Humanoid League soccer rules 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 color patches, respectively.

## 3 Robot Hardware

Two of the humanoid robots that were constructed by the teams are shown in Fig. 4 in more detail. Part (a) shows VisiON Nexta (46.5cm, 3.2kg, 23DOF), which was developed by Team Osaka as successor of the 2004 VisiON robot. Part (b) of the figure shows Jupp (60cm, 2.3kg, 19DOF), which was developed by team NimbRo of Freiburg University. Jupp is based on the technology of its predecessor Toni [6], which reliably kicked penalties at German Open 2005.

All robots that competed in the Humanoid League were powered by electrical motors. Other actuators, like pneumatic muscles or hydraulic cylinders, were not used. In combination with reduction gears and control electronics, electrical motors can be found in RC servos, where a potentiometer measures the actual joint angle and a control loop tries to match the desired angle, which is given by a control line. Almost all humanoid robots at RoboCup 2005 were based on servos or similar intelligent actuators. Only RoboSapien did not control the position of its joints. It uses low-cost geared DC motors and parallel springs to generate torques.



(a) (b)

Figure 4: Two humanoid soccer robots: (a) VisiON Nexta of Team Osaka [22]; (b) Jupp of team NimbRo KidSize [4].

Up to two dozen of the actuators were used per robot in order to achieve sufficient movability of the body parts. The VisiON robot has six actuators per leg, four per arm, two in the trunk, and one in the neck. Jupp has also six servos per leg, but only three per arm, and one in the trunk. The six leg servos used by most robots correspond to the six degrees of freedom for the motion of the foot relative to the trunk. It can translate in three orthogonal directions and rotate around three orthogonal axes. One servo is usually used as knee joint. Its flexion results in leg shortening. Two orthogonal servos form the hip and ankle pitch and roll axes. The position of the yaw joint varies from the most proximal (above the hip as in VisiON), to the thigh (as in Jupp), to the most distal position (at the foot sole, as in KHR-1).

The structure of the humanoid robots is determined by their skeletons, which are mostly made of aluminum and other lightweight materials in order to achieve a good ratio of actuator power and total weight. VisiON was one of the few robots that had a protective cover in addition to the skeleton. Jupp had some soft material on the arms to absorb shocks created by falls.

The robot servos are controlled by small electronics boards, which are usually based on microcontrollers. VisiON uses a 40MHz SH2 controller. Jupp contains three ChipS12 boards, which have a 24MHz HCS12 controller.

The microcontrollers also handle the reading of sensors. In addition to joint sensors, many robots use attitude sensors to detect deviations from the upright posture. VisiON uses two accelerometers and three rate gyros for this purpose. Jupp measures acceleration and turning rate, but only on two axes. To determine the yaw angle, Jupp uses an electronic compass, which is located in its head.

Almost all humanoid soccer robots perceived their environment through color cameras. Only the robots of Toin Phoenix relied on a small laser scanner. In order to cover a wide field of view, the cameras were equipped with wide-angle lenses, were moved, or were pointed towards a convex mirror, which was mounted above the camera. VisiON has such an omnidirectional camera, which constitutes its head. While it allows the robot to see in all directions, the direct surrounding of the robot's feet is outside the camera's field of view. Hence, VisiON had to tilt forward multiple times while positioning itself behind the ball. Jupp's camera is located at its larynx. Its $150^\circ \times 112^\circ$ field of view allows seeing the robot's feet and at the same time looks above the horizon.

The camera images are processed by a miniature PC or a PDA, which also controls behavior and handles wireless communication. VisiON uses a small Pinon embedded PC that has a 400MHz AMD Geode processor. Jupp has a FSC Loox 720 Pocket PC in the trunk. It contains a 520MHz Intel XScale processor.

Most robots were powered by Lithium polymer rechargeable batteries. Despite their low weight, such batteries are able to deliver high peak currents, necessary for some movements. VisiON uses four cells (14.8V) with 2.3Ah. For Jupp two cells (7.4V) with 2.0Ah last for 30 minutes of operation.

# 4 Software

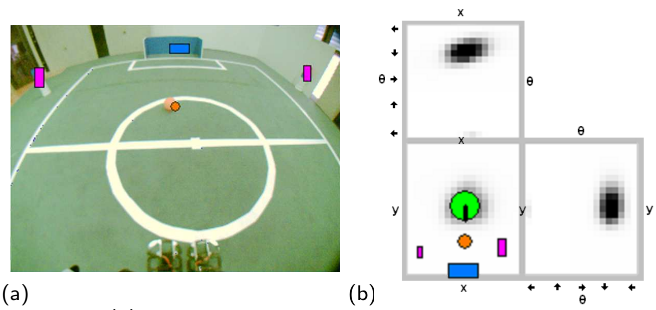
The best robot hardware is worth nothing if it is not programmed to solve the task at hand. To play soccer, three main software modules are needed: perception, behavior control, and communication.

## 4.1 Perception

Perception covers proprioception, exteroception, and exproprioception. Joint sensors, such as potentiometers, encoders, force sensors, and current measurements, are used for proprioception. The robots determine the position of their body parts, relative to the trunk, measure joint velocities, the load, and so on. The individual measurements can be aggregated, e.g. to estimate the length of a leg.

Exteroception of the soccer world is mostly based on visual inputs. The captured images are analyzed to extract the relevant information.

Fig. 5(a) shows an example image from a wide-angle camera. The pixels are classified by color and aggregated to objects, such as ball and goal. It is important to ignore in this process interferences, which might be caused, e.g., by shadows or by the view behind the field border. Attitude sensors, compasses, and proprioception are used to determine the camera perspective. By inverting the camera's projection function, egocentric object coordinates can be estimated. They suffice for basic soccer behaviors, such as positioning behind the ball. For more complex behaviors, such as team play, self-localization on the field is needed (exproprioception). This is done, e.g., by integrating the observations of landmarks (goals, poles, field lines) and motion commands over time. A model of the field is used as map-input for localization. Fig. 5(b) illustrates probabilistic self-localization by a 3D Markov grid [9]. The robots can determine their pose (position $(x, y)$ and orientation $\theta$) even when individual observations are noisy or ambiguous.



(a) (b)

Figure 5: (a) Image captured by a walking robot. In the middle of the bottom the robot's feet are visible. Detected objects: goal (blue hor. rect.), ball (orange circ.), and field markers (magenta vert. rect.); (b) three 2D projections of the 3D grid representing the probability of robot poses $(x, y, \theta)$. Note that $\theta$ wraps around at the borders. The green circle indicates the estimated robot position $(x, y)$ and the black line shows the estimated orientation $\theta$ of the robot.

## 4.2 Control

Based on the perceptions, behavior control decisions must be made to influence the world such that the ball enters the opponent goal more often than one's own goal. Several abstraction layers can be distinguished in the control systems.

Individual joints, e.g. the left knee, reside at the lowest layer of this hierarchy. Fast control loops (e.g. at 300Hz) try to match target and actual joint angles. The behavior of the Dynamixel actuators, used in VisiON, can be configured by a set of parameters. Jupp's servos can only be relaxed.

At the next canonical level of abstraction are the body parts, e.g. the left leg. By controlling individual joints in a coordinated way, e.g., leg extension, leg angle, and foot angle can be changed independently. The resulting joint target angles are smoothed with 180Hz in Jupp's microcontrollers. VisiON generates joint targets at a rate of 60Hz. The abstract actuators that configure body parts are well suited to implement walking behaviors, which are located at the next control level. This level considers the entire robot.

• **Walking:** Most robots in the Humanoid League rely on trajectory tracking methods [12, 17] to generate walking. Trajectories for individual joints or for the zero moment point (ZMP) [21] are generated offline, e.g. by solving the dynamic equations of motion. High gain position controllers are used during walking to follow the predefined trajectory.

A completely different approach to walking is to utilize the robot dynamics. McGeer showed that planar walking down a slope is possible without actuators and control [16]. Based on his ideas of passive dynamic walking, actuated machines have been built recently [8]. They are able to walk on level ground. Since their actuators only support the inherent machine dynamics, they are very energy-efficient. Furthermore, they are easy to control, e.g. by relying on foot-contact sensors. The only participating robot that significantly utilized the robot dynamics was RoboSapien, which was constructed by Tilden [20]. RoboSapien swings its upper body laterally in order to lift its heavy feet.

For Jupp, a gait engine generates omnidirectional walking, which can be parameterized by walking speed, walking direction, and turning speed [3]. This gait target vector can be changed while the robot is 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. Jupp's Pocket PC executes the gait engine at 83Hz. Fig. 6 shows the trajectories generated for forward walking and the resulting robot motion.

In contrast to the continuous walking of Jupp, the VisiON robot concatenates motion macros. It makes brief stops after each motion to ensure continuous transitions between the macros. VisiON's walking and turning motions have been computed by using inverse kinematics. Other behaviors, such as bowing and hand waving, have been designed with a motion editor.

The walking behaviors are used, e.g., to position the robots behind the ball. It is important to rely on visual feedback for frequent updates of the gait target vector because the exact motion of the robot cannot be assumed and also because the game situation can change quickly.

Of course, to play soccer, more behaviors are needed. They include the kicking of the ball, the defense of the goal, and the avoidance of obstacles.

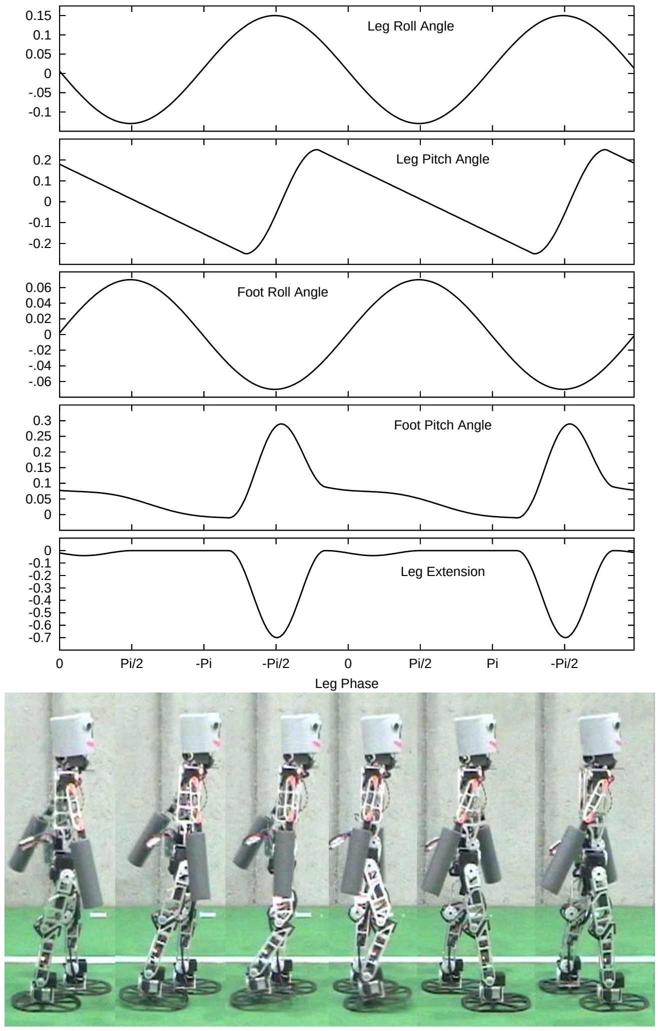



Figure 6: Trajectories for forward walking of robot Jupp.

• **Getting Up:** For a robust system, behaviors are needed that handle exceptions. 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.

Fig. 7 shows VisiON and Jupp getting up simultaneously from a supine position. VisiON lifts its arms and legs while lying on its back. It moves the contact points closer together and pushes itself into a bridge-like posture. Then, it twists its trunk to maintain ground contact with its right hand while raising its upper body. When the COM is inside the foot-polygon, it untwists and straightens its body. As Jupp does not have a yaw joint in its trunk, it cannot perform such a statically stable getting up sequence. Instead, it uses a dynamic motion phase to

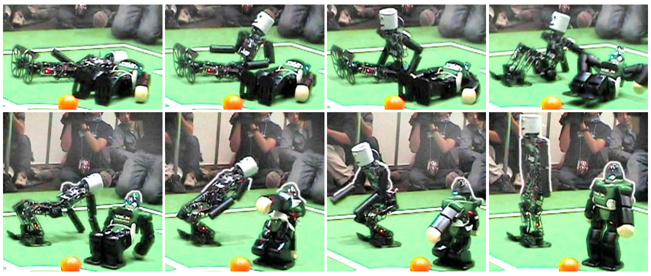


Figure 7: Getting up of VisiON and Jupp.

come from a bridge-like position to a position where the COM is above the foot polygon [18].

### 4.3 Communication

The highest level of abstraction is the control of the team behaviors. Here, roles are assigned to the individual players to ensure that not all robots are heading for the ball, that the goal is defended, and so on. So far, only very basic team behavior has been used in the Humanoid League.

In the communication module the internal and external flow of information must be managed. Multiple microcontrollers communicate within a robot via wired busses (e.g. CAN, RS485) or point-to-point links (RS232) with each other and with the main computer (PC or PDA). These connections are quite reliable. Target positions and aggregated sensor reading are transmitted at a high rate.

For the communication between the robots a wireless network (WLAN) is used, which belongs to the field. The wireless communication is unreliable, though, because many wireless devices are operated simultaneously at RoboCup competitions. Hence, it is important that the robots continue to play when the wireless communication breaks down. If the communication between the robots works, the players tell each other, e.g., the position of the ball or negotiate who takes the initiative to approach the ball.

## 5 Conclusion and Outlook

The Humanoid League is the most dynamic league of RoboCupSoccer. Within few years the performance of the humanoid soccer robots increased to a level that now permits soccer games.

Several teams at RoboCup 2005 were able to reliably kick penalties. The goalies of Team Osaka und Rope (Singapore), which played the penalty kick final in the KidSize class, impressed the spectators with their speed. Team Osaka won the final 5:0.

The penalty kick final in the MidSize class was played by NimbRo and Aria (Iran). As shown in Fig. 8(a), the robot Max of team NimbRo was able to reliably approach the ball, to aim for a goal corner, and to kick it into the goal. NimbRo won the final 3:0.

The KidSize robots also played 2 vs. 2 soccer games. Team Osaka and NimbRo met in the final. NimbRo played with two field players, so that frequently three players were close to the ball, as shown in Fig. 8(b). While the robots of both teams could walk reliably when not disturbed, the physical interaction

(a)

(b)

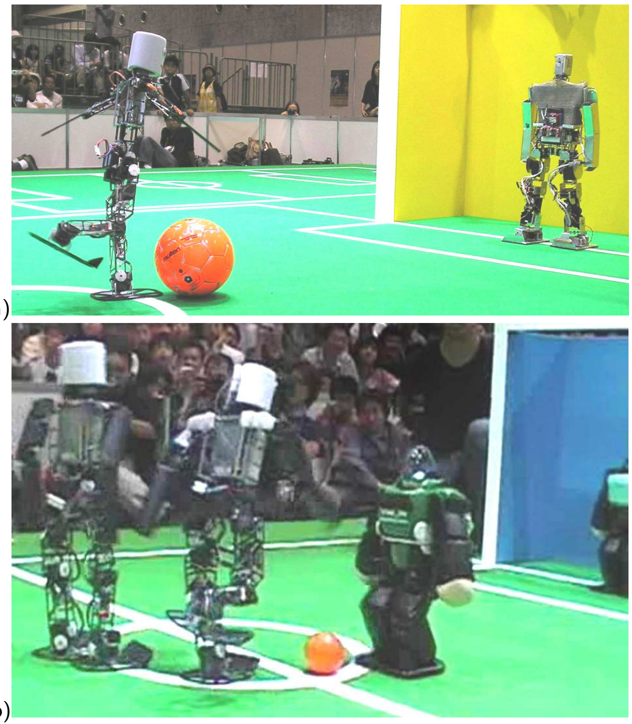


Figure 8: RoboCup 2005: (a) Penalty kick final in the MidSize class (NimbRo vs. Aria); (b) Final of the 2 vs. 2 soccer games in the KidSize class (NimbRo vs. Team Osaka).

of the robots caused some falls. After a fall, the robots of both teams were able to get up by themselves again. Osaka scored twice with distance shots. NimbRo could catch up in the second half of the game with a shot into the goal corner that was too quick for Osaka's excellent goalie. Osaka won the final 2:1.

Team Osaka also excelled in the technical challenge. The VisiON robot completed all three parts of the challenge, which consisted of a walk across a stepping field, the slalom walk around three randomly placed poles, and the kicking of the ball against a fourth pole. NimbRo came in second with its KidSize robot Jupp and third with its MidSize robot Max. This order (Team Osaka, NimbRo KidSize, and NimbRo MidSize) was also the result of the overall Best Humanoid ranking.

The next RoboCup competition will be held in June 2006 in Bremen, Germany, parallel to the FIFA World Cup. The Humanoid League rules have been revised [2]. While the number of robots per team in the competition soccer games will stay at 2 vs. 2, 3 vs. 3 demo games are planned for Bremen. The field size was enlarged to $4.5m \times 3m$ (KidSize) and corner poles were added to facilitate localization. New technical challenges require the robots to dribble the ball around three poles and to pass the ball back and forth between two robots.

Playing soccer with humanoid robots is a complex task, and the development has only started. I expect to see the rapid progress continue in the Humanoid League. Many research issues, however, must be resolved before the humanoid robots reach the level of play shown in other RoboCupSoccer leagues. For example, the humanoid robots must maintain their balance, even when disturbed. The measured robot tilt and the force distribution on the feet might be used as input for postural responses.

In the next years the speed of walking must be increased significantly. At higher speeds, running will become necessary. The visual perception of the soccer world must become more robust against changes in lighting and other interferences. In some years the robots should be able to play without the color coding of the ball and the goals. They should avoid fouls, trick the opponents with feints, and so on. As the basic problems of bipedal locomotion, perception, and ball manipulation are solved better, it should be possible to develop team play.

Among the biggest challenges will be 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 is 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 most attention in future research.

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