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RoboCup: 10 Years of Achievements and Future Challenges

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■ Will we see autonomous humanoid robots that play (and win) soccer against the human soccer world champion in the year 2050? This question is not easy to answer, and the idea is quite visionary. However, this is the goal of the RoboCup Federation. There are serious research questions that have to be tackled behind the scenes of a soccer game: perception, decision making, action selection, hardware design, materials, energy, and more. RoboCup is also about the nature of intelligence, and playing soccer acts as a performance measure of systems that contain artificial intelligence—in much the same way chess has been used over the last century. This article outlines the current situation following 10 years of research with reference to the results of the 2006 World Championship in Bremen, Germany, and discusses future challenges.

A World Championship of Soccer-Playing Robots

Starting with the vision of the RoboCup Federation, we briefly discuss the major differences from former AI challenges and outline the federation's statement. The last section consists of some statistics for the RoboCup competitions.

The Vision

The vision of robots playing against humans has presented many challenges. Robots should be able to handle situations without the need for human assistance. They have to interpret a given situation and use their skills accordingly. Given the nature of this dynamic environment—which demands decisions in real time—background knowledge is also essential. This requirement has been underestimated for a long time now and is especially needed if robots are one day to play against humans. Robots should act appropriately, too; that is, although they can use their bodies, they must not cause harm to humans. The robot's performance must therefore be restricted in order to adapt to the situation of cooperating with a human, for example. The robot should have soft surfaces rather than a hard metal or plastic body, it should have roughly the same weight as a human, it should not be faster than a human, and so on. In a way, the situation is like conducting the Turing test while restricting the computer to a certain computational power. If indeed we are able to create machines of this kind, then we will also be seeing them in everyday situations. We may see robots working with the fire brigade, sitting in a street car, and so on. Technologically, these new robots will require the development and application of new materials, sensors, and actuators. In addition, we must also address the issue of energy. RoboCup is thus an interdisciplinary long-term project.

Many researchers in the community are confronting the question of whether we will actually be able to achieve this vision one day. The uncertainty is part of the attraction of the challenge. Looking back, for example, to the aircraft industry of 100 years ago, researchers could then only dream of the machines that nowadays carry millions of passengers through the air every year. Back then, researchers also had to find new materials and new technologies. Competition played a significant role and was one of the driving forces behind the development.

Chess or Soccer?

One of the primary questions RoboCup raises is that of the nature of intelligence. Some 50 years ago, we believed that intelligence depended on the speed of computation. The

RoboCup is an international joint project to promote AI, robotics, and related fields. It is an attempt to foster AI and intelligent robotics research by providing a standard problem where wide range of technologies can be integrated and examined. RoboCup chose to use soccer game as a central topic of research, aiming at innovations to be applied for socially significant problems and industries. The ultimate goal of the RoboCup project is "By 2050, develop a team of fully autonomous humanoid robots that can win against the human world champion team in soccer." In order for a robot team to actually perform a soccer game, various technologies must be incorporated including: design principles of autonomous agents, multi-agent collaboration, strategy acquisition, real-time reasoning, robotics, and sensor-fusion. RoboCup is a task for a team of multiple fast-moving robots under a dynamic environment. RoboCup also offers a software platform for research on the software aspects of RoboCup. One of the major application of RoboCup technologies is a search and rescue in large scale disaster. RoboCup initiated RoboCupRescue project to specifically promote research in socially significant issues.

Figure 1. The RoboCup Statement.

ability to play chess for example was considered to be a key to understanding intelligence. Everyday intelligence—something everybody is capable of—has been totally underestimated, and as a result, many of the dreams for AI from the 1950s failed. A comparison between chess and soccer reveals that the requirements for playing soccer are closer to those needed in everyday situations. It is also significantly harder to meet these requirements when using computer-controlled machines.

Chess has inspired the effort to create a machine with artificial intelligence, and there have been various approaches to achieving this goal. In the end, the brute-force approach was successful, resulting in the 1997 match in which Deep Blue beat Garry Kasparov. The complexity of chess is undoubtedly high. In the end, however, search methods were able to handle these requirements. Feuilletonists could, however, comfort the shocked audiences with the statement that the computer was not *really* intelligent as such.

Soccer-Playing Robots: RoboCup

Computer programs that can play chess did not, however, answer the question regarding the nature of intelligence. Dealing with everyday situations, the combination of and interaction between body and intelligence and the integration and combination of various methods were challenges in the mid-1990s. Researchers were seeking a new long-term vision, and thus the idea of RoboCup as a testbed for AI and robotics was born (see figure 1).

Friendly competitions have often driven technical advances—the automobile and aircraft industries provide prominent examples. Competitions have been used as test and evaluation platforms in the creation of new solutions.

Another area for autonomous robots is a catastrophe scenario in which robots locate victims in areas that cannot be accessed by humans (mostly due to dangerous situations such as gas, heat, collapsing buildings, and so on). RoboCupRescue offers a thorough test platform for this kind of scenario. Another application area is that of everyday environments such as a typical household. A new test bed that requires special skills was demonstrated at RoboCup 2006: RoboCup@Home. Robots had to fulfill tasks such as opening a door, following a human, and so on. The vision also includes taking care of the next generation. One of the areas of RoboCup is therefore designed for children and younger people: RoboCupJunior.

Competitions

The first RoboCup world championship was held in Nagoya, Japan, in 1997. Annual competitions, accompanied by a scientific symposium, have been carried out ever since, and the community is still growing (see figure 2). Starting with 42 teams in 1997, by 2006 there were approximately 450 participating teams. In 2006, the number of participants exceeded the 2500 mark. With a total of 2561 participants—1492 in the senior and 1069 in the junior competitions—RoboCup is one of the largest (if not the largest) robotic and AI events in the world.

Soccer-playing robots attract media, and the RoboCup Federation therefore also takes large sporting events into account when choosing the locations for the annual event (for example, World Cups 1998, 2002, 2006, European Cup 2004, and the Olympic games 2008).

The Robot Leagues

There is still much to accomplish before we can hope to achieve the 2050 goal. In order to compete and indeed cope using the hardware and the technologies from today, several leagues have been created. In 1997 RoboCup had three leagues, the Middle-Size League (MSL), the Small-Size League (SSL), and the Simulation League (SL). Today, with the addition of the Four-Legged League (4LL) and the Humanoid League (HL), the number of soccer leagues is now up to five.

Parallel to the soccer leagues, other leagues were also invented in order to tackle other applications. The RoboCupRescue League was established in 2001 with robots and simulation devoted to rescue scenarios, while the competitions in RoboCup@Home (established in Bremen) demonstrate robots used for daily activities. The RoboCupJunior leagues include competitions in soccer, rescue, and dance. They are designed to foster education in schools and are tailored for students aged 8–18 years.

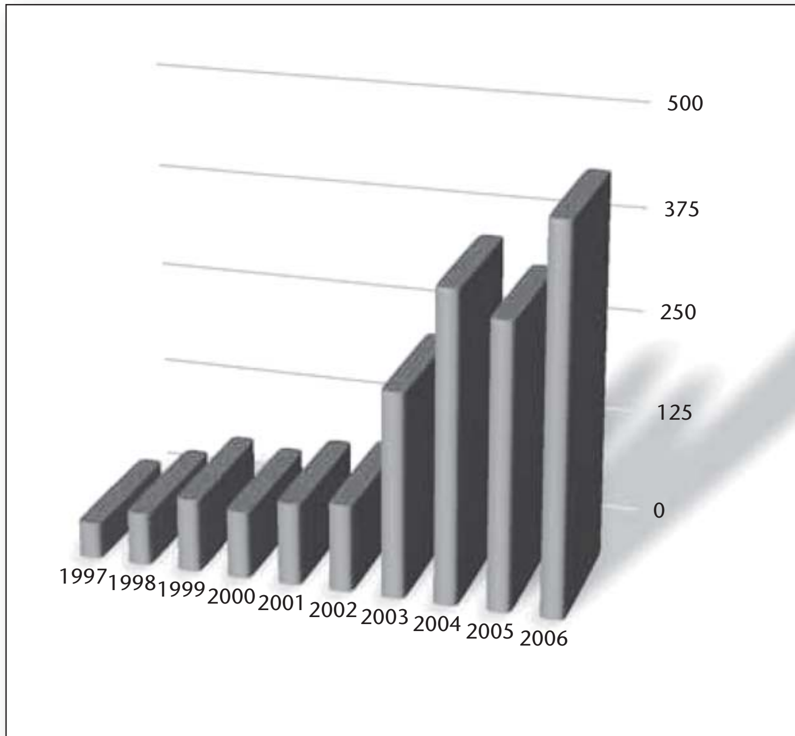

Figure 2. Number of Teams at the RoboCup World Championships.

The Middle-Size League (MSL)

In the middle-size league (MSL), middle-size robots must not exceed a diameter of 50 centimeters, a height of 80 centimeters, and a weight of 50 kilograms (see figure 3). Each robot has individual sensors and control programs. Communication between robots can be achieved with a wireless local area network (WLAN). It is also possible to communicate with an external computer.

Since 1997, several steps have been taken to accommodate various new challenges. In 2002 for example, the barriers around the field were removed and the field size was increased. The lack of barriers also meant that certain sensors used for localization (ultrasound or laser) could no longer be used for that purpose. Nowadays, techniques based on vision (mostly omnidirectional cameras with 30 frames per second or more) take on the task of localization. The six robots per team are able to use separate blue or yellow colored goals, colored landmarks, and white lines on a green field for orientation. Removing the barrier was a big step, given that the robots then had to control the ball to avoid kicking it out of the field.

MSL reports substantial technological advancements. Some teams use big, powerful robots with strong kicking devices. Over the years, however, the use of those types of robots has faded. The tendency now is to build smaller, faster, and lighter robots. Despite other models in the past, an MSL robot nowadays is omniwheeled and omnivisional. The majority of the teams have kicking devices that allow them to kick high and pass over the opponent robots. This makes a whole new range of tactical options possible.

Most of the teams in the MSL have powerful laptops on board. This also means that computationally expensive methods can be used as opposed to a robot in the 4LL, for example. Thus, the most powerful image-processing methods can be found in this league. The demand for environments less conformed for robots has also now been met, for example, with regards to illumination. Since 1997, lighting conditions have been defined (light, colors, ball, goals). As a consequence, methods have improved. In 2006 for instance, we already had variable lighting conditions with one half of the field receiving natural light from outside.

Kalman filter methods seem outdated for use in this league due to the fact that Monte Carlo is gradually taking over localization in practice. The robots can localize various objects in real time now using relatively inexpensive standard hardware. Also with regard to controlling the robots, for example, applying defending and attacking maneuvers, the teams are in good shape. Some attacks, which combine dribbling and simultaneous ball control and high-speed obstacle avoidance, are breathtaking to watch, when measured by any standard. Multiagent scheduling, assignment, and role-picking prob-

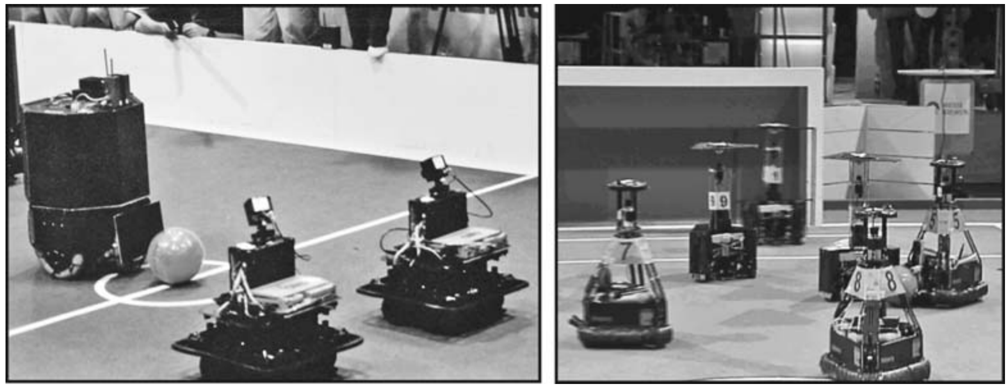

Figure 3. Middle-Size League Robots.

Left: MSL robots from 1997. Right: Robots in the World Cup final 2006.

lems are well understood and can be solved for standard situations. Realistic simulations enabling the performance of coarse-grained training (and learning) have now become possible. The developers of the champion Brainstormers Tribots from Osnabrück (Germany) were already well recognized for their effective results using machine-learning techniques in the Simulation League.

For 2007 the aim is to play outside in the open field. Another challenge will, however, be the integration of mixed teams from different labs, which when combined on site must cooperate in applying their soccer knowledge.

Small-Size League (SSL)

Robots in the Small-Size League (SSL) must not exceed 15 centimeters in diameter. There is a central computer that determines the actions of the whole team, with each individual robot being controlled by radio communication. Two cameras (one for each half of the field) deliver a bird's eye view of up to 100 frames per second, making it possible for the exact positions of the robots to be viewed as well as determining the position and velocity of the ball. Given the central control of the team, good coordination can be achieved.

Since 1997, the environment has undergone enormous change. For example, the field size is now four times as large as it once was. Most of these alterations took place in 2004—when, beside a change of the field size, the walls were removed and auxiliary lights banned. In the first year following this radical change, most teams performed quite badly. Due to the high speed of the robots and the power of most kicking mechanisms, a high level of control and intelligent game play were needed in order to keep the ball on the field and thus keep the game running. By 2006, many teams have succeeded in reaching this level of play.

Increasing the field size also forced teams to use more than one camera. This brought on new challenges concerning the development of techniques for sensor fusion and the efficient processing of growing amounts of image data.

Starting exclusively with the fact that robots have different drives, robot design has evolved incrementally. The current state-of-the-art design for a robot is one with four (in most cases self-made) omnidirectional wheels, enabling velocities of up to 2.5 meters per second to be reached (see also figure 4). The rules concerning ball-handling mechanisms (kickers, chip kickers, and dribblers) have continually been adapted over the years in order to prevent incoherent and rough game play and to enforce more intelligent team tactics.

In general, we have seen a high level of tactical game play by the majority of the participating teams. Most teams were able to play precise passes and to perform well-directed chip kicks and intelligent defense behaviors (for example, one-on-one defense). Some of the top teams even displayed capabilities known as "one-touch soccer" ("1-2-3 passing"), which means that following a pass, the ball is directly shot once again without any interference. The successful application of such capabilities demands a high level of teamwork and robot control. The 2006 tournament was significantly determined by these capabilities rather than by the implementation of simple and straightforward strategies.

Adaptive team strategies, estimation of opponent strategies, and fast cooperative play such as passing and shooting have also been successfully tackled in the small-size league.

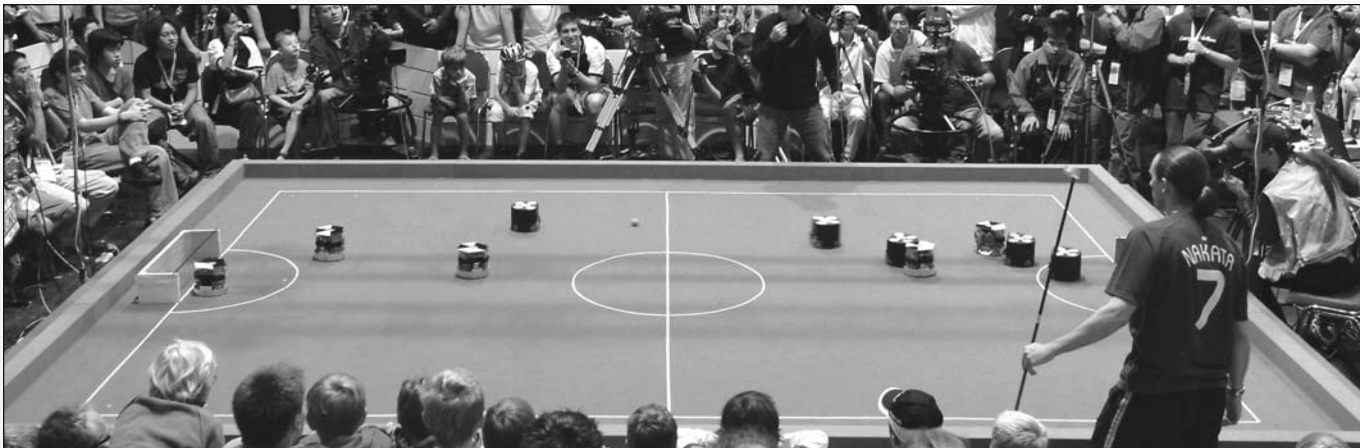

Figure 4. Small-Size League Final.

(5dpo, Portugal versus CM Dragons, USA)

There is however as yet no overall solution, since dealing with a whole team of robots (from the design of the hardware to the development of the software) is challenging in itself and requires many resources. However, with fast and accurate game play, the SSL games have been quite engaging and entertaining this year. This has also been reflected in the large amount of positive feedback and enthusiasm received from the outside community.

In 2006, the winning CM Dragons'06 (Carnegie Mellon University) team reached a new stage of performance with the use of precise hardware and sophisticated software. The team's robots were able to pass with a high ball speed (up to 2.5 meters per second) over several opponents directly to the "feet" of another teammate with a precision of several centimeters.

One of the future challenges for this league is an 11 by 11 game on a larger field. Particularly concerning robot vision, important issues are also color correction for lighting variations across different fields, multicamera fusion, and robust tracking for handling ball occlusions and estimating flight paths of high kicks. The SSL also must address latency modeling (a good team has a latency of approximately 110 ms) and prediction methods to account for latency.

Simulation League (SL)

The Simulation league consists of a virtual playing ground with the original soccer field size and 11 virtual players per team. The main challenge here is to deal with the problems of cooperation among 11 players. This league was established to explore strategic and tactical behavior of a team. A soccer server simulates the physical world including the bodies of the players. The server transmits interpreted sensor information to the programs of the players, that is, their "brains." The server therefore performs simple perception actions. Players have a restricted view of the scene (adapted from humans), and the received information is noisy. The players' programs can generate an internal view of the situation and can decide on the next action (for example, dash, kick, turn, each of them with a certain power and direction). The server then takes these actions and executes them in the virtual playing ground. A soccer monitor can be attached in order to view the game.

This league implements a multiagent system, and the scenario offers research potential in various areas such as coordination and cooperation, distributed planning, learning of various levels (skills for a single player and team behavior), and opponent modeling. To prevent central control, each player program has to act independently. Communication with the use of short messages is only permitted using a say-command through the soccer server. These programs are available online (sserver.sourceforge.net) and can be downloaded. The league started with a two-dimensional simulation and is now progressing towards a three-dimensional simulation containing a more realistic physical simulation (ODE).

The best teams can now show real soccerlike coordinated behavior. Successful attacks from the wings, offside traps, strategic positioning, and open-space attack instead of direct passing are just some examples of their improving skill. In two-dimensional simulation, cooperative defense ability has improved over the years. It seems that not only individual skills, such as an interception or marking, but also cooperative behavior, such as strategic positioning, have been improved. As a result, the number of tie games has increased, and the differences between teams in terms of goals scored have decreased. To break such strong defenses, the top-level teams have started implementing more cooperative offense strategies, similar to those seen in human soccer.

In the three-dimensional league (figure 5), the top teams had highly developed low-level skills (ball interception, passing, dribbling, high and low goal shots). Some of the best teams employed open-space attack strategies instead of direct passing. We also saw the increasing use of high passes (especially from the wings to the goal area) and high goal shots (also due to increased goal height). The champions of the 2D and 3D leagues, Wright Eagle (University of Science and Technology of China), and FC Portugal, played exciting games.

Coach Competition

Each team is allowed to use a coach program, which can analyze the ongoing game using a global view. Such programs can provide advice to its team during the breaks (for example, while the ball is outside the field lines), and can substitute players (a maximum of three times)—an important development given that players get tired and have varying levels of skill with regard to kicking, running, and power. A special coach competition has been established to evaluate intelligent advice from the coaches. In addition, automated commentators exist and are used to provide live commentary on games in an appropriate manner.

The coach programs within the coach competition begin by analyzing the previous-game log files of a given fixed two-dimensional team.

The strategy used by the coach consists of several patterns. In the first step (offline analysis), the coach has to detect specific patterns (simple behaviors) from the log files. In the next step (online detection phase), the coach must detect patterns that are activated in the fixed team. The coach then advises its team during several full matches against a fixed opponent. The coaches should then detect the play patterns of the fixed-opponent in each game and report on them. The coach can send useful advice to its team members to ensure that the detected patterns are correctly followed. The performance of a given coach is based solely on its ability to detect these patterns. The year 2006 marked the second year in which the coach competition was held using this format.

The winner of the coach competition in 2006 was the MRL team from Iran. Comparing the results of the 2005 and 2006 competitions, the teams' abilities in modeling and the detection of patterns had improved. There was marked progress in feature selection and generation, and also in behavioral pattern modeling and detection. However, there is still much to be done.

The coach competition initially started in 2001. The goal at the time was opponent modeling and team adaptation. Between 2001 and 2004, the measure of the coaches' performance was based on their score differences. Merely scoring more or receiving fewer goals did not force teams to apply opponent modeling, so they only used a static hand coded list of predefined amounts of advice. In 2005 and 2006 the structure of the coach competitions was changed so that teams had to detect different playing patterns activated in the opponent team.

The next challenges in the Simulation League concern further improvements of long-term coordination as well as the adaptation of opponents using the coach and automated analysis of earlier games. Players should be able to synchronize their intentions. To get closer to the real robots, new simulation efforts (for example, simulating humanoid robots) are needed.

Four-Legged League (4LL)

Sony's AIBO is the robot that makes this league. One of the reasons for the existence of this league is its platform independence. Every research team has the same type of robot; thus there are no hardware development issues. Thus the 4LL is, in fact, a software competition built for the 576 MHz robots. The AIBO robot type ERS-7 comes with a wireless LAN and has 20 degrees of freedom, and the joints can be controlled with a frequency of 125 Hz. A camera placed at the front of the head offers 30 frames per second with a resolution of roughly 300,000 pixels. Before ERS-7, the teams used ERS-110 and ERS-210 models. The newer types provided better on-board computer and camera performance but also have differing body designs. Therefore, skills like walking and kicking have had to be redesigned. This change has forced the teams to develop related tools using machine learning.

As is the case in other leagues, the rules of the game have changed over the years, always keeping up with cutting-edge technology. The field size has increased to 6 x 4 meters, the walls and the sight protection (see figure 6) have been removed, and the number of landmarks has decreased.

The robots are able to perform numerous

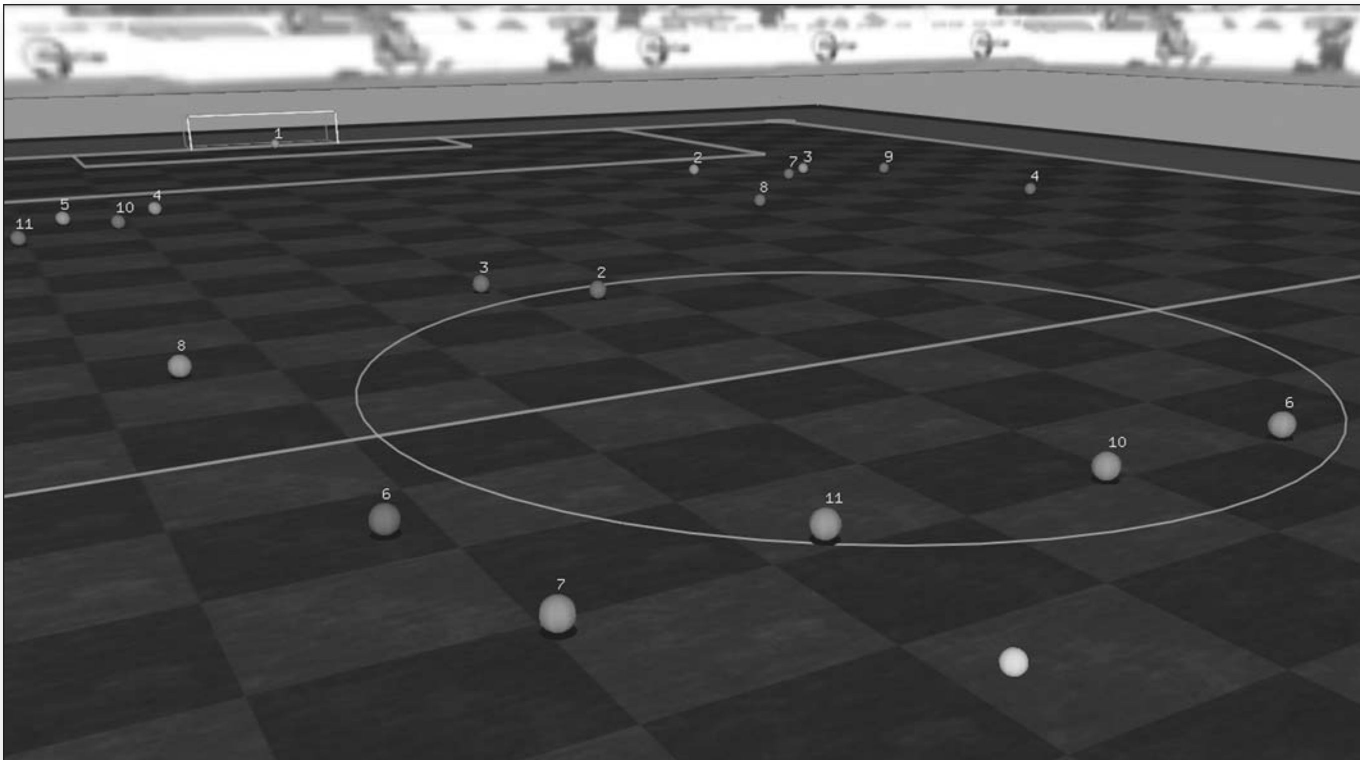

Figure 5. Current View of a Three-Dimensional Simulation League Game

actions due to the number of joints and motors (three actively controlled DOF per leg). The ball can be kicked in almost every direction that it is possible to carry the ball (but only for short periods of time as governed by the rules), and spectacular overhead kicks are also possible. This variation in skills supports the development of methods for planning and action selection.

Begun in 1999, this particular league comprises the most basic skills among the hardware leagues. The 4LL also attracts spectators of all ages and is therefore an important league in RoboCup. However, the announcement by Sony in the spring of 2006 that it was stopping the production of AIBO portends a change in this league. RoboCup Federation is still currently seeking a hardware platform that can replace AIBO—one that is just as ambitious in terms of its perception and action capabilities.

Since every research team works on the same hardware platform, the focus of this league concentrates on perceptions and on methods of controlling the hardware. The robots are getting faster and faster every year due to the improved controls, which are developed using machine-learning methods. The robots can now reach up to 50 centimeters per second. This common hardware platform also fosters scientific exchange—it belongs too to the spirit of RoboCup that solutions and programs are exchanged between the various teams.

We can also now claim new and advanced technological skills. In 4LL, topics and advancements include low-level behaviors, learning, motion detection, and motion modeling. This year, the old question of whether to use a Kalman filter or a particle filter for localization was clearly won by the Kalman filter, since both finalists employed this method. Interestingly, 4LL differs from the Middle-Size League, in which Monte Carlo–based methods are preferred. A step towards collaborative world modeling was demonstrated in the presentation of the Microsoft Hellhounds where a blind robot was controlled by two seeing ones. The German Team showed that AIBO robots could actually play soccer with a black-and-white ball instead of an orange one. This is challenging because the on-board camera of an AIBO is rather limited. TsinghuaHephaestus, a team from China, demonstrated the ability to localize on the field without colored landmarks.

A demonstration game with 11 AIBO robots per team on a middle-size field was held in Bremen for the first time at a RoboCup World Championship. The existing programs from the 4LL had been adapted to the larger field size. The experiment demonstrated individual-

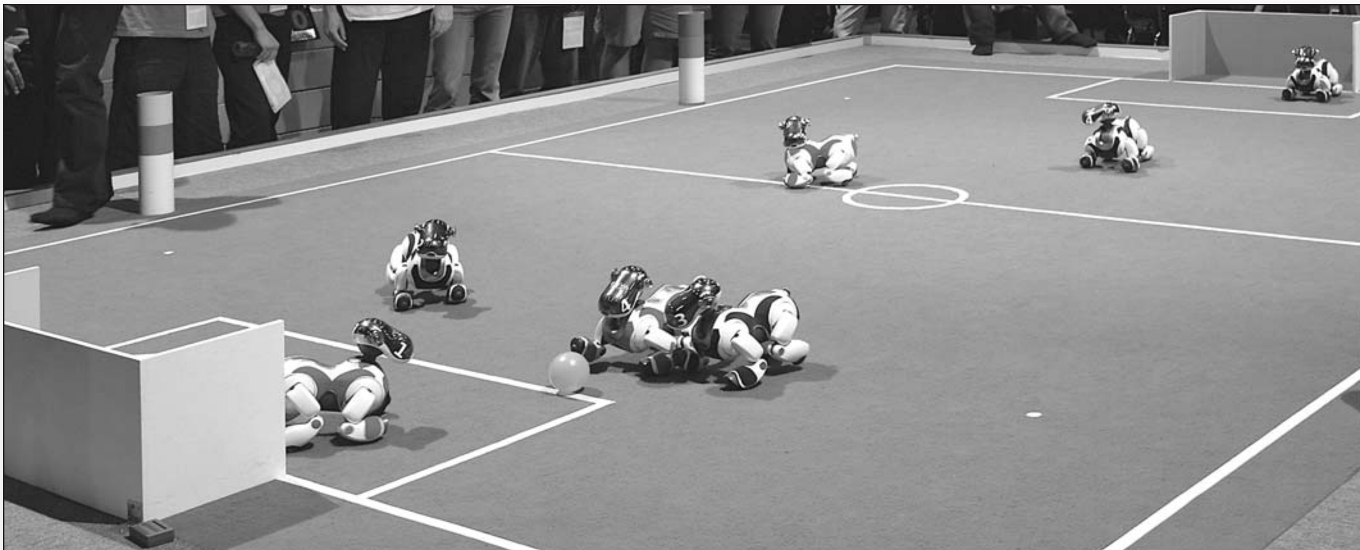

Figure 6. A Scene from a Semifinal of the Four-Legged League 2006.

rUNSWift (Australia) Versus Microsoft Hellhounds (Germany).

istic styles of play, since no efforts had been taken to improve cooperation with more players. Nevertheless, localization and ball handling were performed as well as on the small field.

The champion NUbots (University of Newcastle, Australia) team was superior due to its precise perception and action. Most of its matches ended with very clear results. It is interesting to note, too, that in all real robot leagues the results of most matches appear to be very clear-cut, for example, 6:0 or even more in only 20 minutes. This occurs even between very good teams. These results are possibly explained by the small fields on which teams can often exploit small advantages in a straightforward way. In contrast, matches between above-average teams in the Simulation League often result in draws.

Humanoid League

A humanoid robot has humanlike proportions and appearance: one head, one body, two arms, and two legs. Two different robot sizes exist—the child-sized robot with a maximum height of 60 centimeters and the teen-size robot, which has a maximum size of 120 centimeters. The robots are also restricted to a maximum foot size, and a minimum height of the center of mass or the length of the arms.

The quick technological advancements within the RoboCup community can be best described in this league. In 1998, during the RoboCup World Championships in Paris, Honda's P2 (predecessor of ASIMO) kicked the ball, while the world watched. The robot was remotely controlled and should not have fallen down under any circumstances.

The RoboCup Humanoid League started off in 2002 with demonstrations of single skills such as walking or a penalty shoot-out. These technical challenges still belong to the competition; however, since 2005 we have also seen 2 versus 2 games on a field that is similar to the 4LL field in terms of size and colored landmarks.

The robots on the field have to act autonomously as in all RoboCup soccer leagues. Human intervention is not allowed, and even when robots fall down (which happens very often), they must get up by themselves (otherwise they are penalized). More than 30 percent of the kid-size robots were able to accomplish this in 2006. Goalies were able to jump or fall into one of the corners of the goal in order to catch the ball (first seen in 2004, two years after the start of the league). Most robots were also able to kick the ball with force without loosing balance. Some teams implemented multiple kicking behaviors applied to different situations. The first teams also implemented stabilizing reflexes such as stop walking, which is a technique used to attempt to regain balance when instability is detected. Some teams also implemented protective behavior if a fall was seen as unavoidable.

Most teams used motion macros with brief stops when changing walking direction and for capturing images. In contrast, team NimbRo (University of Freiburg, Germany) used omnidirectional walking, which enabled its robots to change walking direction and walking speed

Figure 7. Humanoids at RoboCup 2006.

These robots are dominated by constructions based on aluminum, carbon, and servomotors. Prototypes with alternative concepts like artificial muscles (the gray in the left background) are exceptions and were not competing in this case.

smoothly while continuously receiving visual feedback.

In contrast to the other real robot leagues, there has been, up to now, no convergence to standard solutions. The construction of humanoid robots differs from team to team. Some teams use low-cost construction kits. Other teams purchase more expensive commercial humanoid robots. However, most teams construct their robots themselves. While most robots were actuated with the help of small servomotors, the 140 centimeter robot of Pal Technology (figure 7, the black robot on the right in the background) used harmonic drive gears. The teen-size robot, Lara of Darmstadt Dribblers, was constructed to use antagonistic shape memory wires as muscles (see figure 8, the large robot on the left).

Perception (especially vision) of the game situation is realized using methods that have been adapted from other leagues. However, they are not able successfully to avoid collisions and contact with the ground. While some teams used an omnidirectional camera as the main sensor, others relied on directed wide-angle cameras, and the remaining teams used a movable narrow-angle camera to keep track of the ball, the other players, and the field landmarks. No special lighting was used for the fields, and only the ceiling lights of the hall were turned on. Most vision systems were able to tolerate significant additional daylight coming through the windows. The 2 versus 2 finals were played on the center court, where the vision systems had to adapt very quickly to different lighting conditions. Complex mechanical compositions are responsible for new challenges in perception. One of the problems is the determination of the camera position and its direction.

The 2006 champion was once again the winner from last year, Team Osaka from Japan with the robot Vision. It was a dramatic final—the first half had a clear result—4:0 for Team NimbRo from Freiburg—but Team Osaka was able to reach a draw in the second half and finally to win the game by 9:5 in over time.

Future developments will at first concern more reliable and flexible skills. Given the historically fast developments in RoboCup, we should see substantial progress during the next few years. The next step will be the integration of developments from other leagues. Nevertheless, for competitions to reach the level of human players, a long period of development is needed—if indeed this is possible at all. New materials and training methods must be investigated, with the current perception still on a basic level. Thus, RoboCup will remain a big laboratory for investigation and integration of different fields.

Increasing overall system robustness is also a major challenge. On the mechanical side, better actuators are needed that can tolerate shock loads, stronger skeleton structures, and soft protective covers. Professional electronic design and more emphasis on system integration and testing is also needed, as is an overall increase in reliability. On the software side, adaptiveness and learning could be used to improve system robustness.

Most of the institutions participating in RoboCup will probably be unable to sustain the construction of a complete team of sophisticated humanoid robots over a long period of time. As a result, a combination of different humanoids may be developed at various institutions, bringing together one team for the future. Such cooperation will be a challenge in itself, let alone the numerous hardware and software issues that must also be addressed.

RoboCupRescue Leagues

Disaster rescue is a serious social issue, which in the case of RoboCupRescue involves a large number of heterogeneous agents in a hostile environment. There are two leagues operating in this arena: the Rescue Robot League and the Rescue Simulation League. The primary goal of the RoboCupRescue League is to promote research and development in this socially significant domain at various levels, including multiagent teamwork coordination, physical robotic agents for search and rescue, information infrastructures, personal digital assistants, a standard simulator and decision support systems, evaluation benchmarks for rescue strategies, and robotic systems that are all integrated into comprehensive systems for the future. Integration of these activities will create the digitally empowered international rescue brigades of the future.

Rescue Robot League

The competition field itself now has many gaps and debris and requires cooperation among the robots. In previous years the robots did not have to cooperate, as there was only one robot in the arena. In the Rescue Robot League (figure 8), robots now cooperate with each other in order to maximize the overall number of identified victims. Difficulties in cooperation between robots from various teams arise due to the differences in hardware and software. Achieving cooperation between robots in this league is therefore a significant step forward.

A new subleague in the Rescue Robot League was introduced in 2006: the Virtual Robots Competition. This competition is based on the Urban Search and Rescue (USAR)-Sim code developed at the University of Pittsburgh, which in turn is based on the game engine from the commercial computer game Unreal Tournament. USARSim allows high fidelity simulations of multirobot systems. It currently offers the possibility to simulate commercial as well as self-developed robot platforms. USARSim complements the rescue league in an ideal way, with a realistic physical simulation of teams of robots operating within collapsed buildings. On the one hand, it offers the possibility to simulate search and rescue scenarios in which every agent has capabilities comparable with those found on real robots, such as sensing with laser range finders or heat sensors. On the other hand, it opens the door to investigating aspects of autonomous multirobot cooperation on the "sensor level" within unknown and unstructured domains. The latter aspect is of particular interest given the physical robots in the rescue league, which more and more allows for the development of autonomous systems.

The virtual robot competition offers a wide range of challenges since each team can choose the number of robots, the type of robots, as well as whether they have an operator or run robots completely autonomously. As has been seen this year however, the difficulty of running a large number of robots that face nearly the same problems as real robots at the same time, such as simultaneous location and mapping (SLAM), exploration, and coordination, seems to be enough of a challenge. Some teams for instance have in particular focused on team coordination with more than 10 robots and the online merging of maps. Simulation environments are significant for the development of physical robots in every league. Almost all teams develop simulators over years. This year however, teams in the Rescue Robot League have begun using simulators to validate their control algorithms.

Rescue Simulation League

The rescue domain represents a real multiagent scenario since a single agent cannot solve most of the encountered problems. Fire brigades, for example, depend on police forces to clear blocked roads in order to extinguish fires (see figure 9). Moreover, the task is challenging due to the limited communication bandwidth, the agent's limited perception, and the difficulty of predicting how disasters will evolve over time. Therefore, this domain requires a high level of team cooperation and coordination, and so far no general solution has been found.

The purpose of the infrastructure competition within the Rescue Simulation League (RSL) is to foster the development of software components for simulation, such as the simulation of the spread of fire. This is necessary because the teams actually compete against a disastrous environment rather than against each other, as is the case in other leagues. During the infrastructure competition this year, human-in-the-loop interface extensions for the simulator kernel were introduced. These become particularly relevant in utilizing the simulation system for real disaster mitigation, such as the training of incident commanders and disaster data integration.

In the RSL, three major breakthroughs have emerged over the last two years. First, a new, more realistic fire simulator has been introduced, enabling greater agent challenges. For example, buildings can now be preemptively extinguished. Other improvements include the increase in the Kobe city map scale from 1:10 to 1:4, plus a revised and more advanced presentation style of simulation. This new format presents the simulation on three separate screens—one large screen displays the run of each team on the map in three-dimensional format, and on two smaller screens, a two-dimensional view and statistical information are displayed.

Furthermore, locomotion in three-dimensional rescue simulation, for example, reaching other floors by using stairs or climbing random steps, present further challenges—challenges that form the basis for real robot teams to operate autonomously within the real world in three dimensions. The simulation competition also opens the door for researchers to overcome the enormous technical hurdles of running real robots as a team and having to prepare their robot architectures, even in large scale environments.

A special outdoor demonstration (the Rescue Robot Field Test) was organized as a special event at RoboCup 2006 in Bremen, where mobile robots and fire brigades worked together in a simulated hazardous material accident (see figure 10). As an opening attraction of RoboCup, the Rescue Robot Field Test contributed to the general success of the championship by demonstrating the advantages of robot technologies and their potential applications in daily life circumstances. In addition to its value as an effective demonstration tool for the general public, as well as being an appealing scenario for both the press and television, the Rescue Robot Field Test has served as a test bed for the development of advanced robots by various academic institutions and, to a large extent, students and other young scholars.

Figure 8. A Robot from the Rescue Robot League Finds Its Way through the Step Fields

RoboCup@Home

RoboCup@Home, first begun in 2006, focuses on real-world applications and human-machine interaction with autonomous robots. The aim of the league is to foster development of useful robotic applications that can assist humans in everyday life. The league consists of a series of fixed tests and an Open Challenge. The ultimate scenario is the real world itself. To gradually build up the required technologies, a basic home environment is provided as the general scenario. In the first years it will consist of a living room and a kitchen (see the setup in figure 11), but soon it will also cover other areas of daily life, such as a garden or park, a shop, a street, or other public places. Figure 12 shows a living room and a dining room with a robot during the competition in Bremen. This test will become more advanced over time and serve as an overall quality measurement in the desired areas. The tests should feature human-machine interaction and be socially relevant, application oriented, scientifically challenging, easy to set up, cost effective, simple, user friendly, time efficient, and, lastly, be interesting to watch.

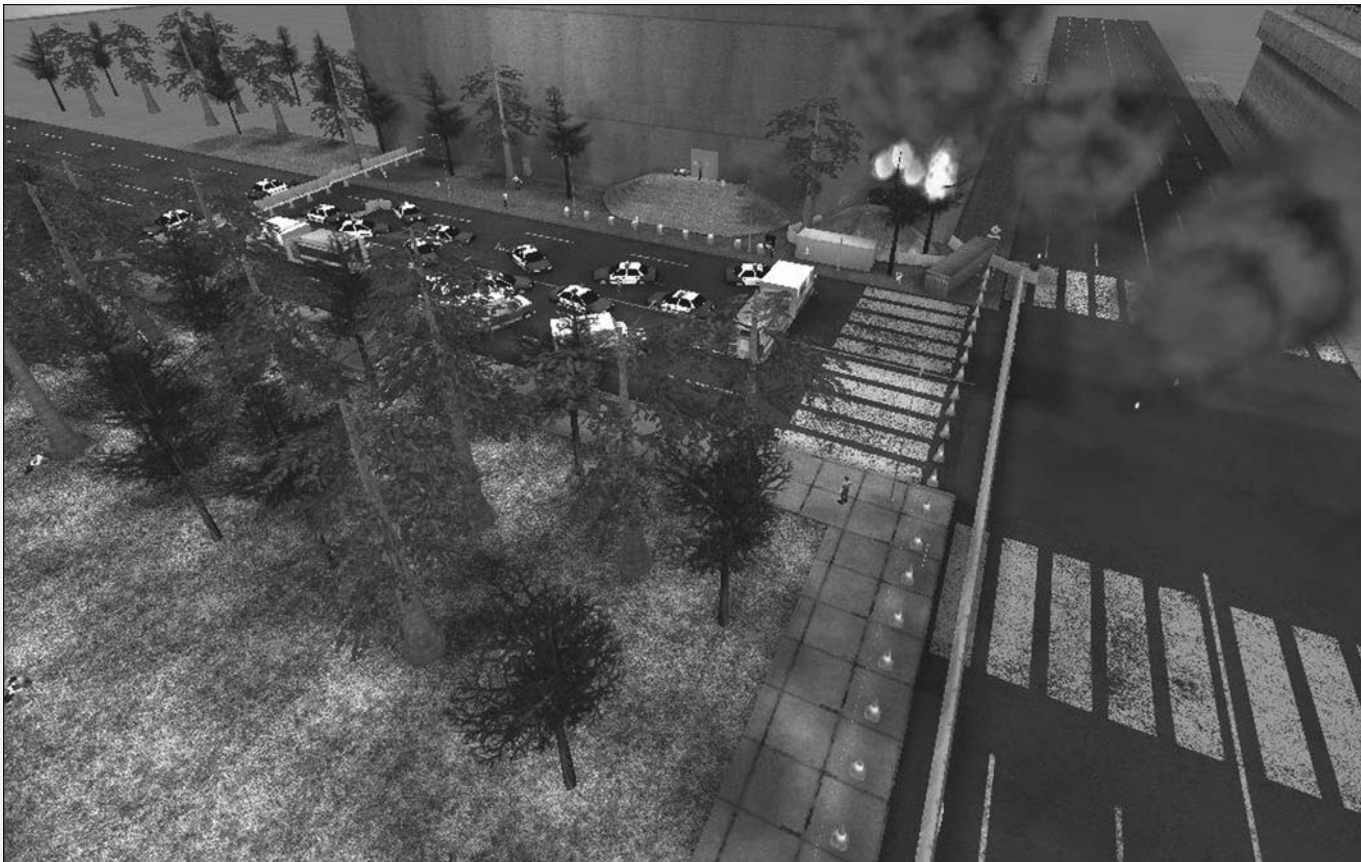

Figure 9: Scene from the Rescue Simulation League.

In the open challenge, freely chosen robot abilities can be displayed and proposals for future tests can actually be presented to the league. According to the criteria of RoboCup@Home, a jury then determines the score and rankings. All robots participating in the RoboCup@Home competition have to be autonomous. During the competition, humans are not allowed to directly (remote) control the robot, but natural interaction is allowed. So for example, joystick, mouse, and keyboard control are not allowed, but speech and gesture commands are. For the early years, headsets will be permitted. Decentralized computing will also be allowed but may be difficult to achieve given general communication problems that could occur during the course of the competitions. The real world presents a high degree of uncertainty, dynamic changes, and variation. In RoboCup@Home environments, a robot has to deal with all these factors. The level of uncertainty will of course too increase over the years in order to adapt to the current environment.

Eleven teams participated at the 2006 competitions in Bremen. Five of them were new to RoboCup and had a background in human-machine interaction. Human-machine interaction was demonstrated with the use of natural language commands. Communication too between the scientists and the audience during the competition has shown to be a successful way to provide an understanding for the motivation behind the robot technology presented. During the competitions, robots were able to cope well with the natural lighting conditions and environment. The robots were able to navigate in unstructured and stochastic environments and to manipulate real objects.

As the tasks in the Open Challenge and the finals are not predefined, a jury had to evaluate the performances by use of defined evaluation criteria. This criteria included presentation, relevance to daily life, human-robot interaction, applicability, ease of setup, autonomy, difficulty, originality, success, and scientific value. The winner of the first RoboCup@Home competition was the AllemaniACs team, from Rheinisch-Westfälische Technische-Hochschule Aachen, Germany, which used one of its MSL robots to perform in this league. The jury was particularly impressed by the precise, fast, and robust navigation displayed, including dynamic path planning and obstacle avoidance.

Figure 10. Mobile Robots Work Together in a Simulated Hazardous Material Accident.

Team Germany 1 is a joint German RoboCup rescue project from University of Osnabrück, University of Hannover, and Fraunhofer IAIS. The team demonstrated two platforms at the outdoor event. The robot shown on the picture is based on a commercial platform from Telerob.

It is, however, worth mentioning that 45 percent of the registered teams within this league actually had a background in human-machine interaction, with the others stemming from the robotics area. Communication and exchange between these teams and the teams already active in RoboCup will on one hand help them to foster an understanding of the special demands of a robot competition (with respect to robustness of the robot systems and the organization of teams) while on the other hand will allow for a gaining of new input from the field of human robot interaction (which, up until now, has not directly been addressed in the RoboCup initiative). Issues encountered during the RoboCup@ Home Competition include intuitive, human-machine interaction, manipulation of physical objects, and people recognition and tracking.

RoboCupJunior

More than 1,000 young people in 239 teams from 23 countries participated in the RoboCupJunior competitions in soccer, rescue, and dance. Soccer is played with one or two robots per team, and the playing ground has different gray scales enabling orientation to be performed using simple light sensors. The ball emits infrared signals, and simple light sensors can localize the ball. The rescue competition consists of line-following with obstacle avoidance and identification of objects. The course also includes an inclined plane. The dance competition is a free-style competition, in which the robots can perform dancing or acting according to a particular story. Often the performances include both humans and robots (see figure 13). A jury then decides on the winner based on various criteria such as technical design, performance value, and aesthetics.

The junior teams may use commercial kits but are also able to use their own designs. The market for related kits is growing in both size and technical aspects (following the developments of technology), and therefore RoboCupJunior is of great interest to commercial firms, particularly in Asia. Numerous awards are given to encourage and motivate development within this area. Recognition is particularly given to those mixed teams from different countries, which were actually formed during the competition.

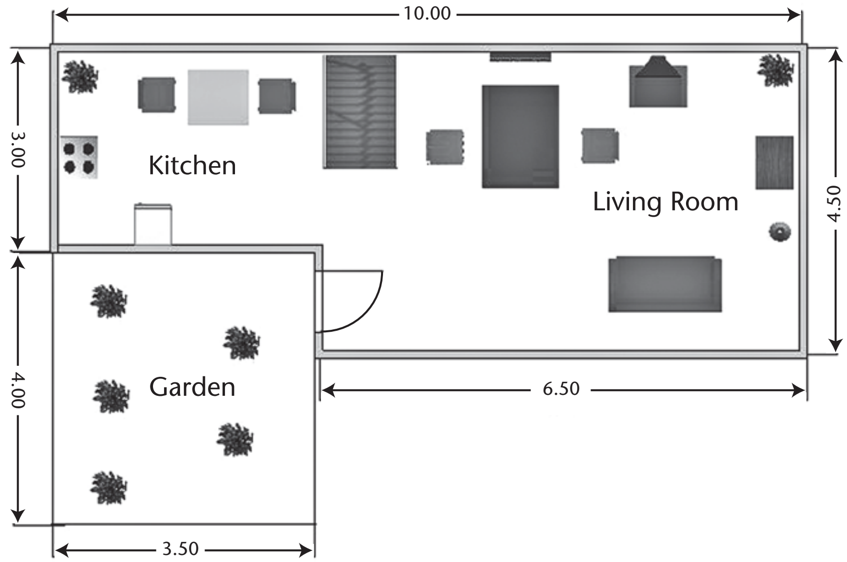

Figure 11. The Setup of RoboCup@Home.

Source: RoboCup@Home rulebook.

RoboCup Competition and Research

The combination of competition and science within the title "RoboCup Championship and Symposium" highlights the scientific claim that the competition is one form of evaluation in which ideas and methods are exchanged. In fact, RoboCup is a platform for (mostly young) researchers, and its success and fast technological advancements over the last 10 years have shown that the concept is effective, intelligent, and extremely relevant. The concept is based on a number of points, which are discussed next.

Long-term goals are written down and are maintained from year to year with a roadmap, which is based on the vision of 2050 but also considers current technical restrictions (for example, battery life, camera resolution, CPU power, and so on) of the market. In this way, the environmental conditions become more and more challenging until they actually resemble the real conditions.

RoboCup events are very costly and by no means comparable to a "normal" scientific conference. One of the issues of the RoboCup Federation is therefore to decrease the expenses by allowing robot play in ordinary environments such as sports halls (as seen in 2005 within the German AI conference) and outside on the green (planned in 2007 for the Middle-Size League).

Ideas, solutions, and also complete software programs have been published providing new teams the chance to obtain the best methods for use on their robots. A prominent example is the code of the German Team (4LL), which won the championships in 2004. A number of teams downloaded the software from the German Team's web page and were then opponents at the same level in 2005. The winner's disadvantage in publishing their secrets is outweighed by the references and citations and, therefore, their enhanced scientific reputation. This is one of the goals of the federation. In addition, the community as a whole benefits from the exchange—the roadmap can be altered towards the 2050 vision as the majority of the robots advance technologically.

The technical challenge can be seen as the technological boundary of RoboCup. The robots have to deal with various technical challenges such as rough terrain or walking with humanoids. One thing that all challenges have in common, though, is that the specific requirements are in fact needed in order to advance to 2050 and as yet are not part of the regular game yet. The roadmap can be changed once a technical challenge is successfully completed by a number of teams. Colocated events such as IJCAI, AAMAS, DARS, and ACTUATORS underline the close relationship to the scientific community.

RoboCup Techniques and Methods

As in other autonomous systems that deal with dynamic environments, a robot must have sensors in order to perceive its environment, actuators in order to manipulate its environment, as well as decision-making algorithms for the selection of appropriate actions. This dynamic environment requires a fast perception of changes (numerous cycles per second), which means that there is only little or no time for a complex processing of all the sensor data. In the early days, researchers in the MSL worked with ultrasound sensors, which have since been replaced by laser sensors. These days, most teams work with methods that are based on camera images (mostly omnidirectional cameras). An important issue is the integration of various sensor data with the time component, which is commonly achieved using probabilistic methods (for example, Kalman filters or particle filters).

In the early days of RoboCup, perception had to be supported by strictly defined lighting conditions and colored landmarks and objects in all leagues. The reduction and stepwise elimination of these means has been primarily tested in technical challenges. Recently, MSL, SSL, and the Humanoid League have been able to achieve play within ordinary illumination situations in indoor halls.

The situation is different in the 4LL since the camera of the AIBO has only a limited sensibility. It has a visual angle of only approximately 57 degrees in width and 42 degrees in height. Therefore, the robots still make use of the color-coded landmarks, which can actually get confused with other objects in the background (for example, people's clothing that has the same colors as the landmarks). Teams try to avoid confusion by taking the horizon into account. The position of the horizon in a particular picture can be determined using the cinematic chain spanning the feet to the head with the camera, but it is subject to error given quick movements, and so on. Alternatives include the use of the field lines, which have already been demonstrated during the challenges between some teams, and actually a further reduction of landmarks has been announced for 2007.

Figure 12: RoboCup@Home.

Robots deal with everyday situations such as a living room environment. They are able to open doors, follow humans, and manipulate real objects.

The removal of the walls (which is now the case in all leagues) has changed the requirements of perception and action, but with differing results. With the use of walls, a strategy as used in ice hockey was useful. Alternatively, the robot could try to push the ball along the walls into the opponents' goal. In fact, the game became often stuck along the walls, since several players tried to push the ball in opposite directions. On the other hand, the removal of the walls created apprehension that the game would be often interrupted because the ball would leave the field. Hence the Humanoid League and the 4LL introduced special restart points instead of a literal throw-in. The ball is placed at a restart point inside of the field, which gives the other team a small advantage.

MSL rules require a throw-in at the place where the ball leaves the field. In the beginning there were many repeated throw-ins because robots failed to carry this task out correctly. Nowadays, however, the robots have well developed skills, and the occurrence of throw-ins has decreased.

In comparison, the Humanoid League had no walls from the very start of the league formation. Teams were also able to use better-performing cameras. Robots using omnidirectional cameras could use it in the same way as the Middle-Size League. Other robots also benefited over the AIBOs due to the higher position of their cameras.

As far as the actuators placed on the physical robots are concerned, there are now more fast and flexible maneuvers. There is a clear prefer-

Figure 13: Performance during the Junior Dance Competition.

ence for smaller robots in MSL due to their displayed superiority in the games over the last years (despite the fact that the larger, heavier systems are more powerful). The various kicking devices—from less successful blowing devices to powerful spring-based devices—did not dominate, as expected, during the games. Until 2005, the ball was played flat on the ground. Since then, and especially since 2006, the majority of the teams can kick the ball in the air, enabling the team to play more efficiently and—in terms of soccer—in more humanlike fashion. This is the case for both SSL and MSL.

The development of the humanoid league is still in its infancy; however, we have already seen rapid progress in terms of the software and construction of humanoid robots. Only three years ago, walking without falling was considered a success. The next significant step was a goal-oriented kick. In 2006, the participating teams made good progress in implementing key soccer skills for their robots. Overall, the walking ability of the robots improved. Walking speed increased, and walking behaviors become more flexible and stable. Keeping balance, especially in critical situations, is still an issue. Balance requires excellent coordination of sensors and actuators. There is a need to think about new ways of dealing with the various problems, to try out new materials (artificial muscles, artificial skin), and to develop new methods in addressing the energy problem. Cooperation between scientists from various fields is also necessary and highly advantageous.

Another distinct kicking skill worth mentioning is the bicycle kick in the 4LL, which was first played by the German Team in 2002. Roughly 30 different kicks have been developed for the AIBO (for all models), ranging from powerful kicks with the head and the body to kicks with the legs in different directions. Further skills also include dribbling and running. The robots must, of course, at all times obey the rule that holding the ball for longer than three seconds is not allowed.

The two-dimensional simulation league uses a simplified simulation of ball handling. The player can determine the direction and power of a kick in the kick command, while the soccer server computes the resulting speed of the ball compared to the last ball's speed as well as the position of the ball relative to the player. Additional background noise is also added. Therefore, the setting is reasonably complicated, and good kicking and dribbling behavior are not easy to perform. Interception of a moving ball is also complicated given that perception of the environment is challenged by noise interference. Varied approaches of machine learning have been used to develop efficient skills for kicking, passing, dribbling, and running. A number of these skills are available in a library for general use.

The three-dimensional simulation league is based on a physical simulation by means of ODE. To date, only very simple player shapes are used. More realistic designs are under development in cooperation with the Humanoid League. However, the performance of computers is actually somewhat restricting. Again, good skills can, however, be developed using machine learning.

A comparison between requirements for a robot in the RoboCup environment and a robot in a traffic scenario yields differing results. Perception is easier in RoboCup because the robots act in a defined environment. Primitive actions, such as braking, accelerating, and steering, however, are easier in the traffic scenario. This means that reactive behavior is possible for the robot, and if there is doubt, the car can actually be stopped. In robotic soccer, however, even primitive actions have significantly more options (particularly with the legged robots) given the different number of degrees of freedom (such as dribbling with a four-legged robot).

Cooperation between robots is still a challenging problem. The only league achieving good results has been the Simulation League. We can learn from this that classical planning algorithms do not perform well in real time or in dynamic environments and that the time issue is critical—a robot has to perceive, to decide, and to act in less than 100 ms. Solutions for these kinds of problems can also be relevant and of interest to robots in the traffic scenario.

The experience in RoboCup over the last 10 years proves that the need for cooperation in robot soccer largely depends on the size of the field and the number of players in a team. Similar to human soccer teams, the Simulation League has a great need for high-developed cooperation strategies. It is interesting to note, too, that the development of these strategies followed the same path as that of human soccer history—it started with static positions of the players, then the positions were dynamically adapted, and now we see increased movement combined with related complex strategies.

In the leagues of real robots, the smaller fields did not force long-term strategic behavior. Only basic cooperation skills like passing were used, and it seems that to a great extent they are sufficient. However, an experiment performed with the 11 by 11 demonstration game in the Four-Legged League has shown that such strategies do not necessarily correspond well across different leagues. Thus, the leagues will soon require increased cooperation when playing larger fields, which will then enable the strategies already developed for the Simulation League to be implemented.

Another difference between real and simulated robots relates to the control architecture. Both robots use layered architectures to a large extent; however, while the real robots require high-output efforts in order to manage both the lower reactive control and short-term goals, the simulated robots are able already to manage advanced levels of control using long-term intentions.

In all areas of RoboCup we have to solve optimization problems within large parameter spaces as well as with the challenge of incomplete and questionable data. Among this, too, are perception problems, such as the determination of ball velocity or opponent modeling, primitive skills such as dash, kick, dribble, as well as complex behavior such as team strategy and tactics. Machine-learning methods have been tested in all of these areas and have proven to be extremely valuable.

Machine learning has played a major role from the very beginning of RoboCup and was first used in the Simulation League. This league still provides a lot of data for machine learning and in addition is often used as a benchmark in the world outside of RoboCup. Machine-learning methods include reinforcement learning, evolutionary methods, support vector machines, neural networks, case-based reasoning, plus many others, often used in combination. They appear on different layers, starting with low-level skills (such as kicking or dribbling), including positioning as well as passing behavior, and ranging up to the level of strategic behavior. Opponent modeling appears once again on the different levels and plays a key role for the coach competitions as discussed previously.

Besides the Simulation Leagues in soccer and rescue, a wide range of tools used for the development, programming, and testing for each of the different real robot leagues exist. Many teams have in addition developed their own tools based on simulations of their team robots in a simulated environment. Since work with real robots is time consuming and expensive, the use of such tools has many benefits. Some of these tools are complete simulations of the soccer games; such is the case in the 4LL. It is possible to test different skills and strategies in virtual reality, and of course they are also very helpful for debugging.

An important utilization of such simulation tools is that of machine learning. Skills in the 4LL and in the Humanoid League need to be optimized in a high dimensional parameter space. The large degrees of freedom allow for many different solutions, and the performance of the robots can therefore be improved every year. Simulation is used for first explorations, which later must then be evaluated and potentially refined and adapted to the real robots. Furthermore, a comparison of new candidates (for example, of new individuals in evolution or of search directions using hill climbing) with existing solutions allows for a preselection process prior to beginning the actual experiments.

In contrast, the experiments with the real robots lead to improvements of the simulation tools, with the ability to forecast by simulation improving each time. Several tools are built around physical simulations resulting in a substantial increase in performance. Nevertheless, the general experience in the RoboCup community demonstrates that simulation is still far away from total substitution of experiments in reality.

The most popular programming language used is C++, although other languages, such as Prolog, are also used by some teams within the Simulation League. Even Java, a language that would not perhaps be an obvious choice when talking about real-time issues and robotics, is used successfully in the Simulation League. Apart from these pure programming languages, other unique languages are used, such as the

coach language in the Simulation League.

Conclusion

RoboCup was invented to tackle general AI challenges. Now, after 10 years, continued development has resulted in significant improvements particularly across the areas of construction, perception, cooperation, and interaction. The integration of all these outcomes and improvements into a complete running system has of course presented various challenges. However, the large number of well-performing teams now in existence demonstrates that a great deal of progress has in fact been achieved during this relatively short period of time. The actual integration of various features and rational behavior with restricted resources is a key problem in understanding (artificial) intelligence at all.

Nevertheless, there is room for development with the large majority of issues in RoboCup, specifically relating to scientific questions as well as technical solutions. Sometimes a gap between the two is taken into consideration, separating low-level features like basic perception and action on the one side and high-level thinking on the other. This could also be considered as the difference between subsymbolic and statistical approaches versus symbolic ones. Past experiences in RoboCup have, however, clearly shown that none of these approaches can solve all issues alone (as is still sometimes claimed). Teams from different leagues have, for example, been able to demonstrate that high-level symbolic approaches lead to advanced behavior when combined with techniques that are based on low-level data. Higher-level approaches describe situations qualitatively. This is also useful in other domains like traffic analysis or cell tracking for cancer cells.

Most of the teams combine their work with other challenges from outside RoboCup in terms of addressing scientific questions as well as technical solutions. The evaluation and the exchange of ideas during the competitions and the symposium is an effective and worthwhile foundation for their future work. To achieve the 2050 vision—*to see robots come head to head with humans in a soccer match*—is not in truth really as important, but it is, indeed, an inspiring goal.

Acknowledgments

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Technical Papers

This article has been written as a report and therefore does not refer to any specific articles. However, all papers presented on the RoboCup symposia, listed by year of publication, have been published as follows:

Bredenfeld, A.; Jacoff, A.; Noda, I.; and Takahashi, Y. 2006. *RoboCup-05: Robot Soccer World Cup IX*. Lecture Notes in Computer Science Vol. 4020. Berlin: Springer.

Nardi, D.; Riedmiller, M.; Sammut, C.; and Santos-Victor, J. 2005. *RoboCup-04: Robot Soccer World Cup VIII.* Lecture Notes in Computer Science Vol. 3276. Berlin: Springer.

Polani D.; Browning, B.; Bonarini, A.; and Yoshida K. 2004. *RoboCup-03: Robot Soccer World Cup VII.* Lecture Notes in Computer Science Vol. 3020. Berlin: Springer.

Kaminka, G.; Lima, P.; and Rojas, R. 2003. *RoboCup-02: Robot Soccer World Cup VI.* Lecture Notes in Computer Science Vol. 2752. Berlin: Springer.

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Stone, P.; Balch, T.; and Kraetzschmar, G. 2001. *RoboCup-00: Robot Soccer World Cup III.* Lecture Notes in Computer Science Vol. 2019. Berlin: Springer.

Veloso, M.; Pagello, E.; and Kitano, H. 2000. *RoboCup-99: Robot Soccer World Cup III.* Lecture Notes in Computer Science Vol. 1856, p. 802. Springer, Stockholm.

Asada, M., and Kitano, H. 1999. *RoboCup-98: Robot Soccer World Cup II.* Lecture Notes in Computer Science , Vol. 1604. Berlin: Springer.

Kitano, H. 1998. *RoboCup-97: Robot Soccer World Cup I.* Lecture Notes in Computer Science , Vol. 1395. Berlin: Springer.

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