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■ RoboCup is an international initiative with the main goals of fostering research and education in artificial intelligence and robotics, as well as of promoting science and technology to world citizens. The idea behind RoboCup is to provide a standard problem for which a wide range of technologies can be integrated and examined, as well as being used for project-oriented education, and to organize annual events open to the general public, at which different solutions to the problem are compared. The eighth annual RoboCup—RoboCup 2004—was held in Lisbon, Portugal, from 27 June to 5 July. In this article, a general description of RoboCup 2004 is presented, including summaries concerning teams, participants, distribution into leagues, main research advances, as well as detailed descriptions for each league.

RoboCup 2004 Competitions and Symposium

A Small Kick for Robots, a Giant Score for Science

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According to the RoboCup Federation, the ultimate goal of the RoboCup initiative is as follows: "By 2050, a team of fully autonomous humanoid robot soccer players shall win a soccer game, complying with the official FIFA rules, against the winner of the most recent world cup of human soccer" (Kitano et al. 1997). As a result of this goal, from 1997 through 2000 robotic soccer matches composed the main part of the RoboCup events. Since 2000, however, the competitions have also included search and rescue robots, thus demonstrating the application of cooperative robotics and multiagent systems to problems of social relevance (Kitano et al. 1999). RoboCupJunior, also introduced in 2000, has now become a large part of the RoboCup event. RoboCupJunior introduces robotics to children attending primary and secondary schools and includes undergraduates who do not have the resources to take part in the RoboCup senior leagues (Lund and Pagliarini 1999).

RoboCup 2004 was held in Lisbon, Portugal, from 27 June to 5 July. As in past years, RoboCup 2004 consisted of the Eighth RoboCup Symposium and all the competitions. The competitions took place at Pavilion 4 of Lisbon International Fair (FIL), an exhibition hall of approximately 10,000 square meters, located at the former site of the EXPO98 world exhibition (figures 2, 3). The symposium was held at the congress center of the Instituto Superior Técnico (IST), Lisbon Technical University. Together with the competitions, two regular demonstrations took place on a daily basis: SegWay soccer, by a team from Carnegie-Mellon University, and Sony QRIO robot, by a team from Sony Japan (figure 4).

Portugal was chosen as the 2004 host due to its significant representation in RoboCup committees, competitions, and conferences—a result of the country's efforts in recent years to attract young people to science and technology. Euro 2004, the 2004 European Soccer Cup, also took place in Portugal at the same time; this collocation improved RoboCup's media coverage.

RoboCup 2004 was locally organized by a Portuguese committee composed of 15 researchers and professors from several universities, therefore underlining the national nature of the event organization. The committee worked closely with the international organizing and technical committees to set up an event that yielded a record number of participants (1,627) from 37 countries, and more than 700 robots, divided among 346 teams.

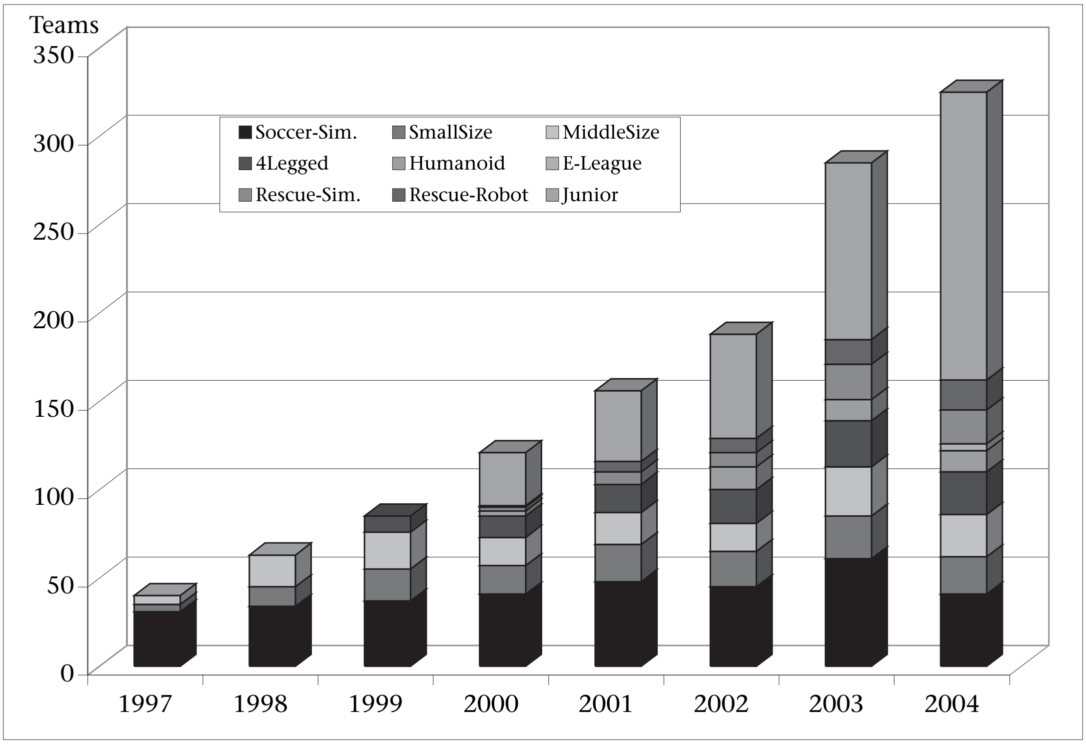

Figure 1. The Evolution of RoboCup in Terms of the Number of Teams.

Figure 1 shows the evolution of RoboCup in terms of the number of participating teams (total and per league). Noticeable is the significant increase in the number of junior teams (163) participating in RoboCup 2004. In comparison with RoboCup 2003, the number of senior teams in RoboCup 2004 declined, due to participation restrictions that were instituted for the first time. However, the number of teams that submitted qualification material was significantly larger than the number of participating teams (a total of 392 senior teams submitted qualification material and a total of 162 senior teams participated in RoboCup 2004).

Twenty technicians from FIL were involved in the preparation of the competition site, and 40 student volunteers aided in the event's execution. The event was hosted by the Institute for Systems and Robotics (ISR), a research institute located on the campus of IST.

There were three primary changes in the RoboCup 2004 competitions: illumination, larger fields, and a new E-League.

Illumination. Common to most real robot leagues (except the four-legged league), illumination was no longer based on spotlight projectors assembled on trusses spotted around the fields but simply on the existing artificial light of the competition site.

Larger fields. Most real robot leagues now have larger fields, which reduces robot density on the field, improves game quality, and fosters strategies based on cooperation.

E-League. Originally demonstrated at RoboCup 2003 as the U-League, the E-League took its place as the newest RoboCup league in 2004. By focusing on high-level issues, the U-League provided an entry point for new teams that had neither the experience nor the resources to participate at the senior league level.

In the following sections we will briefly overview the main research progress this year, the technical challenges faced by participants, and the competition results by league. More details on competitions, including photographs, short video clips, and other related information can be found on RoboCup 2004's official web page.[1]

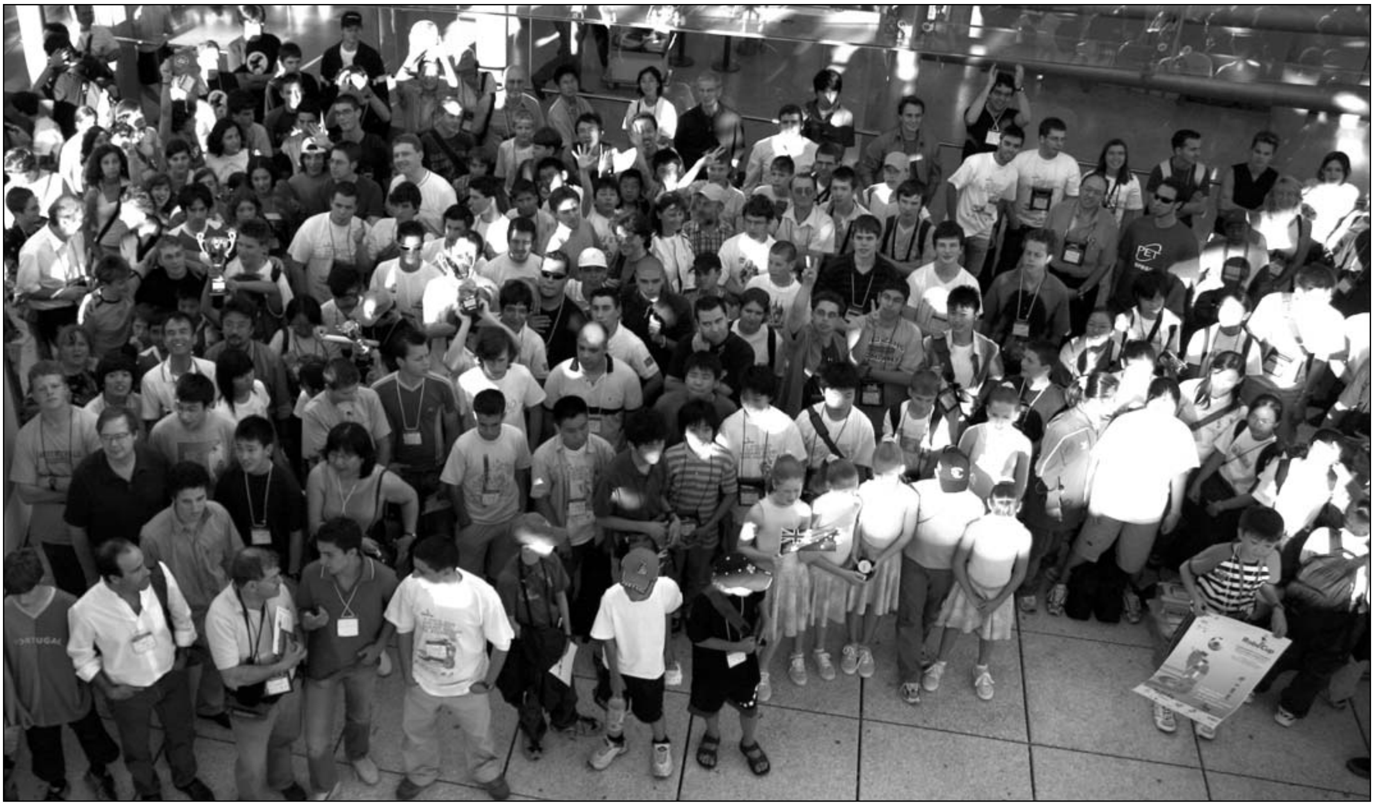

Figure 2. View of Some of the Participants at the Venue's Entrance.

RoboCup 2004 Symposium

The Eighth RoboCup International Symposium was held immediately after the RoboCup 2004 competitions. The symposium served as the core meeting for the presentation of scientific contributions in areas of relevance to RoboCup. Its scope encompassed the fields of AI, robotics, and education.

The International Federation of Automatic Control /European Robotics Research Network (IFAC/EURON) Fifth Symposium on Intelligent Autonomous Vehicles (IAV 2004) also took place at the Instituto Superior Técnico, Lisbon, from 5 to 7 July 2004. IAV 2004 brought together researchers and practitioners from the fields of land, air, and marine robotics to discuss common theoretical and practical problems, describe scientific and commercial applications, and discuss avenues for future research.

On July 5, the IAV 2004 Symposium ran in parallel with the RoboCup Symposium; both events shared two plenary sessions. In one session, James Albus, from the U.S. National Institute of Standards and Technology (NIST), described the well-known and widely applied NIST Real-time Control System (RCS), cognitive architecture, and its applications to multiagent systems. In the other session, Shigeo Hirose from the Tokyo Institute of Technology, Japan, described the development of rescue robots at the Tokyo Institute, with some impressive video demonstrations of real robots.

Two plenary sessions, specific to the RoboCup 2004 Symposium, were presented. Hugh Durrant-Whyte, from the University of Sydney, Australia, discussed autonomous navigation in unstructured environments, with applications to field robotics. Luigia Carlucci Aiello, from Università di Roma "La Sapienza," Italy, summarized the challenges overcome during the past seven years of RoboCup, as well as the new challenges foreseen in the years to come.

On the last day of the symposium, a panel discussed applications of RoboCup research. The panel was moderated by Hans-Dieter Burkhard, and featured Hiroaki Kitano (ERATO Kitano Symbiotic Systems Project, JST, Japan), RoboCup founding president, Christian Philippe (ESTEC/ESA), and M. Isabel Ribeiro (ISR/IST), IAV2004 general chair. Topics discussed by the panelists included biology, aerospace robotics, and land robotics.

A total of 118 papers were submitted to the RoboCup 2004 Symposium. Of those submitted, 30 were accepted as regular papers and 38

Figure 3. Overall View of RoboCup 2004 Site.

as poster papers. Both will be published in the RoboCup subseries of the Springer Lecture Notes on Artificial Intelligence book series.

The Scientific Challenge Award was presented to Cody Kwok and Dieter Fox for their paper "Map-based Multi Model Tracking of a Moving Object," which introduced an approach for tracking a moving target using particle filters. The Engineering Challenge Award was given to Juan Cristóbal Zagal Montealegre and Javier Ruiz-del-Solar for their paper "UCHILSIM: A Dynamically and Visually Realistic Simulator for the RoboCup Four Legged League," which describes a robotic simulator specially developed for the RoboCup four-legged league.

Soccer Middle-Size League

The middle-size league (MSL) this year had 34 preregistered teams, 24 of which were qualified for the official competition. Preregistered teams were asked to submit a team description paper, a video, and a list of publications. The league technical committee evaluated each of the preregistered teams based on the submitted data, and teams were ranked. The top 24 teams qualified.

Competition

The 24 teams were divided into 4 groups of 6 teams each for the first round-robin stage. The top 4 teams from each group qualified to compete in the second round-robin. There, 16 teams were divided into 4 groups again, and the top 2 teams from each group earned a spot in the final tournament. WinKIT (Kanazawa Institute of Technology, Japan), Persia (Isfahan University of Technology, Iran), Minho (University of Minho, Portugal), FU-Fighters (Freie Universität Berlin, Germany), CoPS-Stuttgart (University of Stuttgart, Germany), Trackies2004 (Osaka University, Japan), Eigen (Keio University, Japan), and Brainstormers-Tribots (University Osnabrueck/Dortmund, Germany) survived the preliminary round-robins. Table 1 shows the result of the competition. Omnivision systems and omnidirectional vehicles using omniwheels were popular in this league. Because the vehicles' speed has increased from earlier years, the games seemed more vigorous.

Technical Challenges

To promote the scientific goals of RoboCup, the technical committee holds a technical challenge competition to showcase specific scientific and engineering achievements. For 2004, the middle-size league had two main technical challenges: (1) ball control and planning, and (2) scientific or engineering achievements.

In the ball control and planning challenge, six to eight black obstacles were put at arbitrary positions on the field. The ball was put on the middle of the penalty area line, and a robot was positioned inside the same goal. The robot was supposed to dribble the ball into the opposite goal within 90 seconds, while avoiding all obstacles. The trial was repeated three times with various setups. Team Persia, from Isfahan University of Technology, Iran, won the ball control and planning challenge this year.

In the scientific or engineering achievements challenge, teams were each free to show one significant achievement, while all the other team leaders, along with the technical committee members, judged them. Team Persia also won this challenge. The Clockwork Orange and AllemaniACs (Gönner, Rous, and Kraiss 2005) teams demonstrated their real-time color-calibration method without human intervention and also exhibited good performance.

A "cooperative mixed-team play" challenge also took place in 2004. In this event, teams demonstrated cooperative mixed-team play between at least two robots from different teams. This year, one team consisted of robots almost entirely from German teams while the other team of robots were from non-German teams. Watching the match was very enjoyable, and the robots showed good collaborative play during the game. Nevertheless, it would be interesting to see cooperation among international

Figure 4. Demonstrations.

Top: SegWay soccer; *Bottom:* QRIO mapping its environment.

Rank	Team (Affiliation)
First	Eigen (Keio University, Japan)
Second	WinKIT (Kanazawa Institute of Technology, Japan)
Third	CoPS Stuttgart (University of Stuttgart, Germany)

Table 1. Results of the MSL Soccer Competition.

teams emerge from this challenge, for example, by creating standards for communication protocols.

Research Advances

This year, a considerable number of changes in rules and regulations of the MSL took place. First, the field size was enlarged to 8 by 12 meters. Flexibility in the number of players was added by introducing an area occupied by the whole team as the main criterion for the maximum number of allowed players per team. If a team built smaller robots, it was allowed a larger number of robots on the field during a game. The MSL technical committee expects that this rule change will encourage teams to show more cooperative behaviors (such as passing a ball to a teammate, coordinated defense, and positioning to receive a pass) of their robots, since the chances that those behaviors are advantageous increase when there are a larger number of robots on a noncrowded field. Actually, some robots did try to pass or receive the ball. Unfortunately this maneuver sometimes failed because of the lack of precise ball handling.

Tracking a ball on a large field is a hard problem for vision systems, because when the ball is far from the robots, its image in omnivision systems is very small. In some situations, robots were unable to detect the ball in the distance, resulting in the game becoming stuck. We expect that more efficient vision and cooperative distributed perception systems will solve this problem in the near future.

A referee box system was introduced to convey referee decisions to robot players without intervention from the team operators. In the small-size and four-legged leagues, this technology has already been implemented, successfully enhancing the autonomy of the game. Unfortunately, in the middle-size league, full implementation of the referee box system was delayed; only the start/stop commands were implemented in 2004. Introduction of the throw-in/goal-kick procedures was postponed until 2005. Figure 5 shows a snapshot of an MSL game.

Soccer Four-Legged League

The Soccer Four-Legged Robot League (4LL) is the only RoboCup league in which a standardized robot platform is used—the Sony specially programmed AIBO, a four-legged robot with 20 degrees of freedom with a color camera as its main sensor. Consequently, teams in this league concentrate on developing control software while completely ignoring robot construction issues. By using a common platform, teams gain the ability to exchange code between each other, run the code of other teams on their own robots in practice matches at home, and use one of the most powerful mobile robotic systems available today that is (because it is a mass-produced product) relatively cheap. In addition, the standardized platform allows teams to focus on the development of efficient algorithms rather than on tricky mechanical constructions as is the case in other leagues. For example, teams are forced to solve the problem of selective directed vision, because the AIBO has a single camera in the front of its head that can be moved in three degrees of freedom. This poses many interesting research questions, such as how to decide where to look (active vision), how to self-localize, how to model the objects in the world that are currently not visible, and how to sense and model the world using multiple communicating robots.

Competition

In 2004, three of the 23 teams that participated in the competition were national teams consisting of members from more than a single city—an accomplishment that is, although not impossible, hard to realize in leagues with self-built robots. In addition, the two new teams in the competition—the Hamburg DogBots and the Dutch Aibo Team—based their software on the previous year's code of the GermanTeam. This code reuse allowed the Hamburg DogBots to reach the quarter final. However, 2004 also was the competition with the largest diversity in robot platforms because Sony released a new AIBO during the summer of 2003—the ERS-7, which is significantly stronger than its predecessor, the ERS-210. In fact, only a single team using the old model reached the quarter final.

The eight best teams reached the quarter final with impressive goal differences, the average of which was 31-4. However, despite the strong competition, the two finalists, UTS Unleashed! (University of Technology, Sydney, Australia) and GermanTeam (Humboldt Universität Berlin, Universität Bremen, Technische Universität Darmstadt, Universität Dortmund, Germany) won their quarter and semifinals de-

Figure 5. A Middle-Size League Match.

cisively (UTS Unleashed! 9-1, 5-1, GermanTeam 9-0, 9-2). In a close match, the GermanTeam won the final against UTS Unleashed! 5-3. The abilities of the two teams' robots were quite different. While UTS Unleashed! had stronger single players that won many duels, the GermanTeam had better positioning of the robots and a very strong goalkeeper. The three first places of the 4LL Soccer Competition are shown in table 2.

Technical Challenges

Traditionally, there are three technical challenges in the four-legged league. For the first time in 2004, an Open Challenge was introduced, in which teams were encouraged to demonstrate parts of their research and have the demonstrations assessed by the other teams. The demonstrations included robot collaboration, ball handling, object recognition, and tracking by vision or sound, and so on. The Open Challenge was won by the GermanTeam, demonstrating four robots moving a large wagon. The four robots were controlled by the fifth robot on top of the wagon to score a goal with a middle-size league ball (figure 6). The second challenge was the Almost SLAM Challenge, in which a robot had to learn some unknown colored landmarks in its surroundings and later perform metric self-localization using them. This challenge was won by rUNSWift (University of New South Wales, Australia), who reached four of five possible positions within a range of less than 50 centimeters. In the third challenge, the Variable Lighting Challenge, a robot had to score as many goals as possible within three minutes, under changing lighting conditions. This challenged seemed almost insurmountable, because even the winner—ASURA (Kyushu Institute of Technology, Japan)—only scored two goals. The overall winner of the technical challenges was UTS Unleashed!

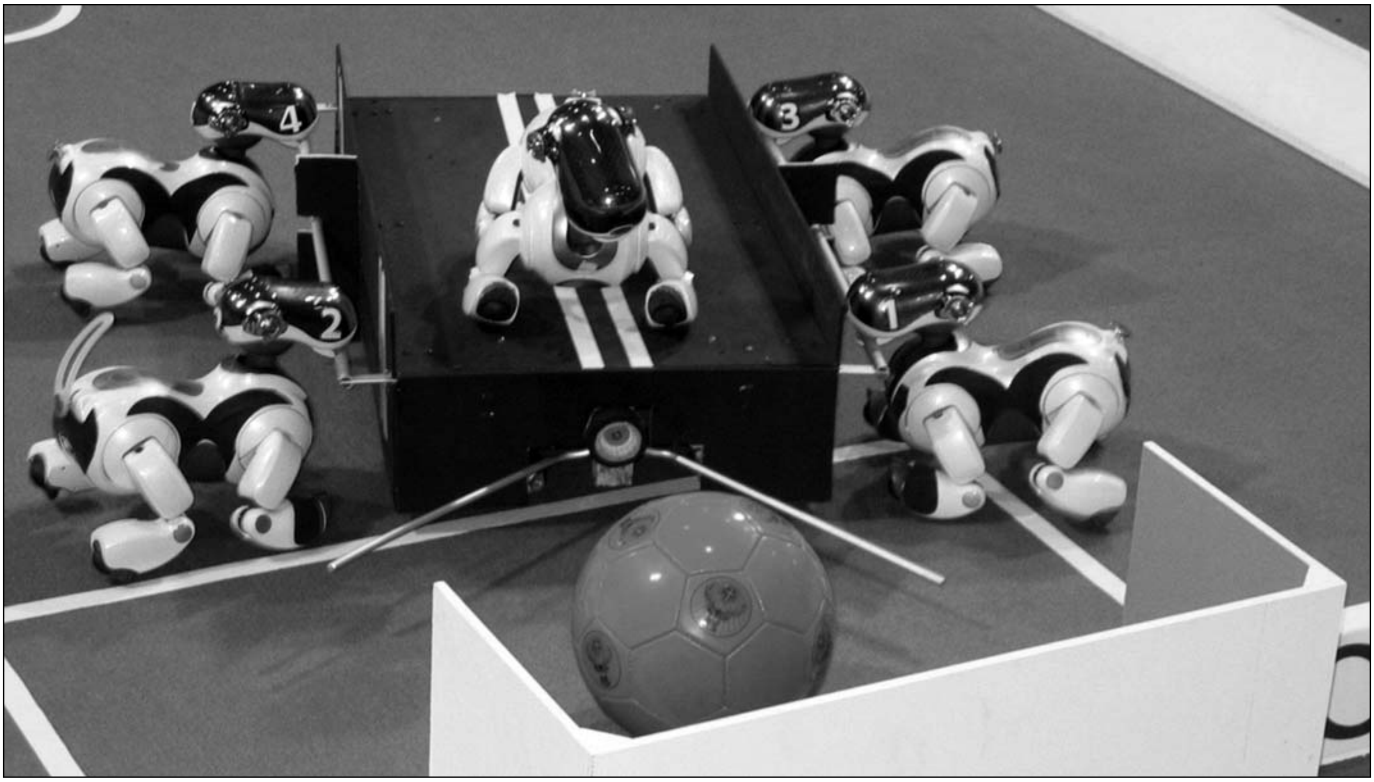

Figure 6. 4LL Open Challenge: Four Robots Controlled by a Fifth One Score a Goal.

Rank	Team (Affiliation)
First	GermanTeam (HU Berlin, U Bremen, TU Darmstadt, U Dortmund, Germany)
Second	UTS Unleashed! (University of Technology, Sydney, Australia)
Third	NUBots (University of Newcastle, Australia)

Table 2. Top Three Teams in the 4LL Soccer Competition.

Research Advances

As in past years, some rules were modified to increase difficulty for the teams. A major change was the replacement of the obstruction rule by the field player pushing rule. This change meant that instead of removing passive robots that block the way to the ball for others without going for the ball, robots that pushed against other robots were penalized if they were not the closest robot of their team to the ball. This rule change forced the implementation of obstacle avoidance. It was implemented because of the 2003 success of the Obstacle Avoidance Challenge (Hoffmann, Jüngel, and Lötzsch 2005). The rule change improved the games significantly, because there was considerably less crowding of robots around the ball (as an example, it was not necessary to call field player pushing in the final).

Another rule change was the removal of the two center beacons, which made self-localization more difficult, especially for the goalie. The purpose of this rule change was to force teams to work on self-localization using the field lines (Seysener, Murch, and Middleton 2005), a concept that had already been demonstrated by the GermanTeam at RoboCup 2003 (Röfer and Jüngel 2004). GermanTeam significantly benefited from this ability at RoboCup 2004, because its goalie was localized very well and the field players were only rarely called for entering their own penalty area (a movement that is not allowed). For instance, in the finals, the robots of UTS Unleashed! were penalized nine times for being an illegal defender, while the robots of the

GermanTeam never committed this infraction.

Another rule change that required self-localization was one requiring full autonomy; that is, the robots had to walk to their kickoff positions on their own. This ability was not implemented by all teams because the penalty for ignoring it was minor.

Besides improving self-localization, there was quite a push toward research on gait optimization in this league (Kim and Uther 2003; Quinland, Chalup, and Middleton 2003; Kohl and Stone 2004; Röfer 2005). As a result, the games were significantly faster. For instance in RoboCup 2003 the fastest gait was 27 centimeters per second. By 2004, using the new robots, the fastest gait had increased to 41 centimeters per second. Another observation was that now many teams were able to estimate the speed of the ball to perform blocking moves, using either extended Kalman filters or Rao-Blackwellised particle filters (Kwok and Fox 2005). The use of three-dimensional (3D) simulations is also becoming common in this league—even physical ones (Montealegre and Ruiz-del-Solar 2005).

Soccer Small-Size League

In the small-size league (SSL), teams of five robots play against each other on a green carpet field. The robots are restricted to a height of 15 centimeters and a diameter of 18 centimeters. Color cameras mounted over the field allow an external host computer to see the entire playing field and decide the action of each player robot. Commands are relayed to the robots by means of radio frequency. Color markers on top of the robots are used to identify individual robots. The official ball is an orange golf ball.

Competition

A total of 21 teams from 11 countries competed in the RoboCup 2004 SSL competition. Two of the teams were joint teams with members from different countries. In the preliminary round, teams in 4 groups played in a round-robin fashion. The top 2 teams from each group proceeded to the playoff stage. The winners of the competitions are listed in table 3.

Rank	Team (Affiliation)
First	FU Fighters (Freie Universität Berlin, Germany)
Second	Roboroos (University of Queensland, Australia)
Third	LuckyStar (Ngee Ann Polytechnic, Singapore)

Table 3. Top Three Teams in the SSL Soccer Competition.

Research

There were three major changes to the SSL this year. First, no special lighting was provided for the playing field. Teams had to cope with the dim and uneven lighting at the RoboCup venue. Many teams had a hard time calibrating their global vision systems to the bad lighting. Many were surprised by the dark shadow cast by the camera-mounting structure and were not prepared for it (figure 7). In the end, all teams were able to play, but vision-related problems were noticeable during many of the matches. Due to the excellent lighting conditions of past years, many teams had been able to make do with simple vision algorithms, and vision research was generally neglected in SSL. We will probably see more teams working on improving their vision systems in the future.

Second, the new playing field of 4 by 5.5 meters was slightly more than twice the area of the previous field. The intent of this change was to open up the space, thus encouraging more passing during the game. There was also a new rule restriction on dribbling to discourage an individualistic style of play. Some of the teams were observed to make a few purposeful passes during matches, and some of these passes did result in a big advantage for the team. We hope that next year more passes and more sophisticated passes will happen.

Third, the field boundary walls were removed, thus simulating a more human football-like environment. This change reduced effective match time to less than 40 percent for most matches, because the ball left the field too readily. One of the major challenges for teams in the league will be to play a more controlled game, thus keeping the ball in play more often. This challenge will require better ball control, more precise shooting and passing, and a more intelligent form of play.

Most teams had similar mobile bases—basically the four-wheel drive omnidirection system introduced by Cornell in 2002. The four-wheel design affords good traction capability, and many team robots were able to move at speeds above 1.5 meters per second with high acceleration and deceleration. A few teams introduced a "chip kick" mechanism, which allowed the robot to kick the ball over opponent robots. Currently, chip kicks aren't accurate, either in distance or direction control, and they resulted in the ball going out of field most of the time. The FU Fighters robot, however, performed both chip and normal straight kicks powerfully. The team achieved this by ingeniously squeezing two different kicking mech-

Figure 7. Kick-off During an SSL Match.

Note the dark shadow cast by the camera-mounting structure on the right side of field. The shadow posed a big problem for many teams' vision systems.

anisms into the tight body space of the robot. Coupled with the team's high speed and precise robot control, the FU Fighters won all its matches.

Despite the major rule changes introduced this year, the teams competed well. Most teams were unable to take advantage of the increased field size because of the efforts required in adapting to the new rules. With only minor rules revision expected next year, teams will have more time to work on new team strategies that take advantage of the bigger field space.

Soccer Humanoid League

The humanoid league (HL) made its debut at RoboCup 2002 and has been one of the most interesting highlights of RoboCup since then. The challenges in this league are different from other leagues. Unlike others, the main challenge in the HL is to maintain dynamic stability while the robots are walking, running, kicking, or performing other tasks. Furthermore, the perception and biped locomotion of humanoid soccer robots must be coordinated and robust enough to deal with challenges from other players. The HL is expected to provide the main thrust toward fulfilling the challenge of developing a team of fully autonomous humanoid robots that can win against the human world soccer champion team by the year 2050 (Kitano et al. 1997).

Participation in HL at RoboCup 2004 was encouraging. There was a significant increase in

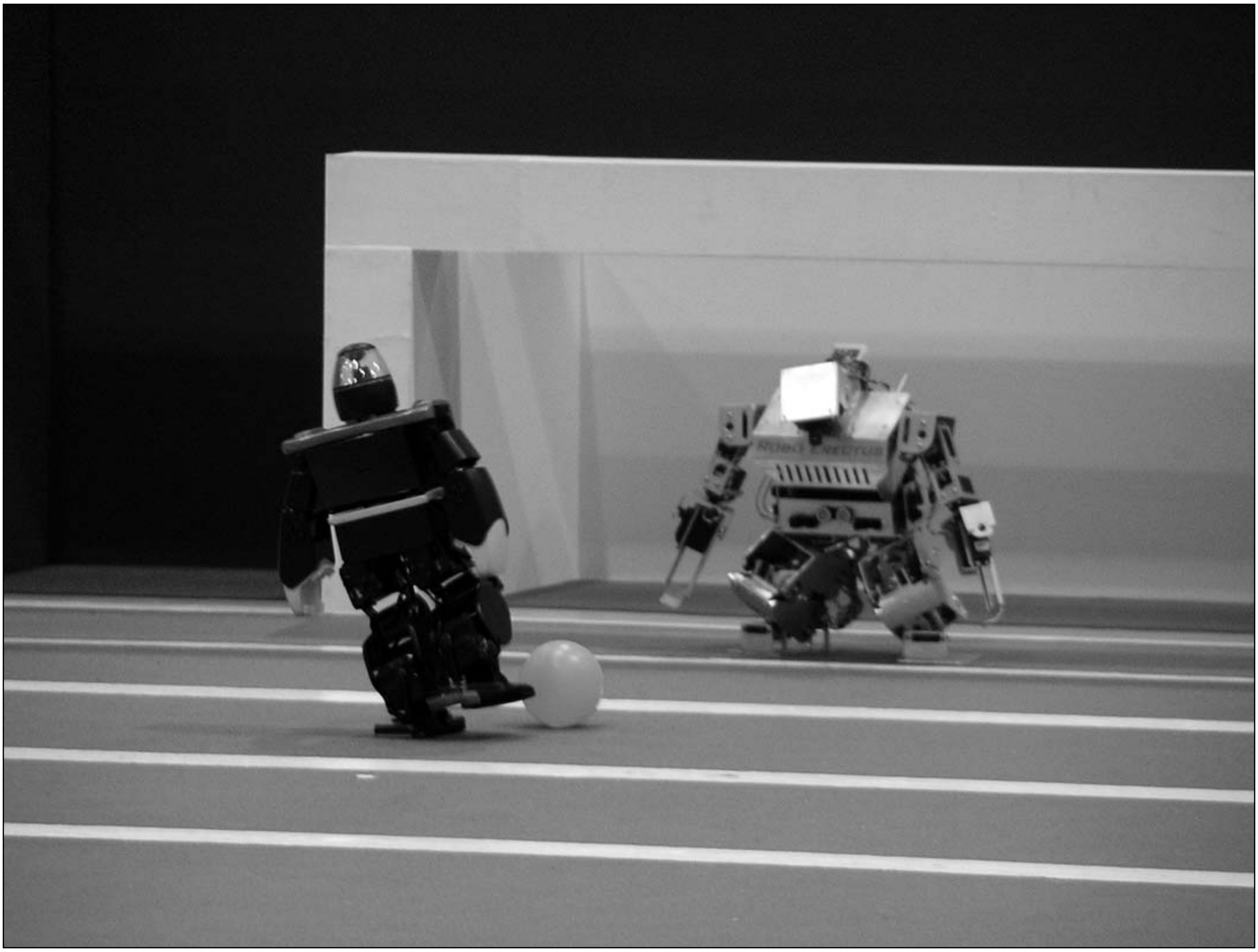

Figure 8. Penalty Kick by Team Osaka's ViSion Robot.

the number of countries and number of teams indicating interest in taking part in the competition. For the first time, a qualifying selection had to be made. After the qualifying round, a total of 16 teams from 6 countries were selected to take part in HL. For the first time, there were participating teams from Iran and Germany.

Competition

The competition consisted of three nongame disciplines (Zhou, 2004), namely, humanoid walk, penalty kick, and freestyle. In additional to the above traditional competitions, technical challenges, including obstacle walk, balancing-on-a-slope walk, and ball passing, were conducted for the first time at RoboCup 2004.

A number of excellent robots were presented in the competition. After some good and hard-won matches, Team Osaka emerged as the overall winner (figure 8). It received the Best Humanoid Award as well as the Technical Challenge Award. Winners in the other categories were as follows: In the humanoid walk category, the winner was Team Osaka (Systec Akazawa Co., Japan). The winner of the humanoid freestyle was Team Osaka (Systec Akazawa Co., Japan). The 80 cm. humanoid penalty kick winner was Senchans (Osaka University, Japan), and the winner of the 40 cm. humanoid penalty kick was Team Osaka (Systec Akazawa Co., Japan).

Research Advances

The year 2004 marked the third year for the HL competition. Tremendous improvements were witnessed in numerous aspects of the participating humanoid robots. In the following paragraphs we examine some of the features of humanoid soccer robot technology.

Mechanical structure and materials: The mechanical structure of the robots has been greatly improved with better designs and lighter bodies (using innovative material like carbon alloy) and supporting a more ergonomic look.

Walk: The robots' ability to walk on uneven terrain was tested in the balancing walk on a slope—a technical challenge conducted for the first time this year. Tremendous improvement in the walking speed of the humanoid robots was also observed. The humanoids were required to start at one end of the field, walk to the other end, turn around at a marker placed in the middle of the area, and return to their initial position. The distance between the initial position and the marker was 5 times the height of the humanoid. The best completion time in 2004 for the humanoid walk competition was 50 seconds—a far cry from the 2002 best time of 3 minutes, 29 seconds.

Kick: Striker capability in detecting the ball and changing the direction of kicking in response to the goalkeeper's position were noted in the penalty kick competition this year. The diving capability, the ability of the goalkeeper to change the diving direction in response to the kicking direction of the striker to save the goal and the ability to stand up again after diving, was observed for the first time this year in the penalty kick competition.

Passing: Ball-passing capability was observed in the ball-passing technical challenge, and the ball-passing demonstration between two robots by the team from Osaka University was particularly impressive.

Manipulation: Whole body coordination was demonstrated by many robots in their ability to stand up from a lying down position and in various dancing and upper body movement demonstrations.

Power: Most of the robots this year came equipped with an internal power supply.

Communication: Several robots this year came with wireless communication capability, either in the form of Bluetooth or a wireless LAN. Multimedia integration was also noticed in some robots.

Perception: The introduction of an omnivision system in a humanoid robot was made by Team Osaka's ViSion robot. Whether this vision technology should be introduced to humanoid robotics remains an open question, however. Coordination of perception and locomotion was demonstrated in 2004 through the capability of some robots to perform various actions in response to the environment, either in the humanoid walk, penalty kick, or technical challenge competitions.

For the next few years, dynamic walking will surely be the most interesting challenge in the humanoid league. The best humanoid robot is still significantly slower than an average human.

Looking back at the HL in 2004, it can be seen that there are some areas in the humanoid robots where improvements are still needed. Battery technology still falls short of expectations—most robots require internal battery changes after a brief period of activity. There is also room for improvement in on-board computing. In addition, humanoid robot locomotion is still far from perfect; the best humanoid robot is still significantly slower than an average human, and improvements are still needed for versatility in movements, an increase in the speed of locomotion, implementation of jumping, running movements, and so on. Finally, vision and recognition also need to be improved.

Beginning next year, in the penalty kick competition, the ball will no longer be placed at a fixed position but instead will be put in a number of locations. This change will call for higher perception capability. Of course, most of the robots are far from being robust. Many of them will still hang and malfunction at times. Safety also remains a problem for most of the robots.

Overall, essential soccer skills were demonstrated in the HL competition this year. Looking to the future, one-against-one and two-against-two soccer games that require humanoid collaboration will be initiated soon.

Soccer Simulation League

In the RoboCup Soccer Simulation League, two teams play against each other over a local network. Each participant connects 11 player agents and possibly a coach agent to the server, which simulates the soccer field and distributes the sensor information to the agents. The newest development in the Soccer Simulation League was the introduction of a new simulator, where players are spheres in a three-dimensional environment with a full physical model. A prototype of this new simulator was introduced to the community during the RoboCup 2003 Symposium (Kögler and Obst 2004). The simulator was further developed throughout the year (figure 9). The time between the first release of a usable version in January until the qualification deadline in March was sufficient to allow 15 teams to qualify and participate. In addition to the new three-dimensional competition, the "traditional" two-dimensional (2D) competition was kept, and 32 teams participated. For the first time in the 2D competition,

	3D Simulation	2D Simulation	Coach Competition
1.	Aria (Amirkabir University of Technology, Iran)	STEP (ElectroPult Plant Company, Russia)	MRL (Azad University of Qazvin, Iran)
2.	AT-Humboldt (Humboldt University Berlin, Germany)	Brainstormers (University of Osnabrueck, Germany)	FC Portugal (Universities of Porto and Aveiro, Portugal)
3.	UTUtd 2004 (University of Tehran, Iran)	Mersad (Allameh Helli High School, Iran)	Caspian (Iran University of Science and Technology, Iran)

Table 4. The Top Three Teams in the Soccer Simulation League Competitions.

qualification for participation was held in the Internet League, where participants upload their teams to a server. In the Internet League, matches against other teams are scheduled and started automatically. The coach competition, composed of 7 teams, was the third competition in the Soccer Simulation League. In this competition, participants had to provide a coach agent that could direct players from its team using a standard coach language. Coaches were evaluated by playing matches with a coachable team against a fixed opponent. The countries with most participants in the Soccer Simulation League were Iran, Japan, and Germany.

Competition

The participants in the 3D simulation eagerly expected the first match. It was exciting to see how the teams used the basic agent capabilities of the new simulator to navigate on the field and move the ball. Agents in the 3D simulation can move in any direction, but because of inertia and the delayed effects of motor commands, methods used to approach a moving ball are not straightforward and were handled differently. Despite the short development time, some of the participants managed to implement not only low-level skills like intercepting the ball and dribbling but also team-level behavior like passing and cooperative handling during special situations. Lessons learned in 2D were apparently transferred to the 3D league, so that some of the matches looked already very advanced.

The team with the best game play was UTUtd 2004 from Iran (Mahmoudian et al. 2004). This team ended up taking third place after an unfortunate loss to AT Humboldt from Germany in the semifinal, where AT Humboldt scored the golden goal (the first team scoring a goal wins). Developers of AT Humboldt (Berger, Gollin, and Burkhard 2004) built their 3D team using the same flexible architecture used for their 2D teams, so that it was possible for them to improve their performance between the first day and the finals. The top three teams in the Soccer Simulation League competition are shown in table 4.

Research Advances

In the 2D competition, teams employed many approaches, and there is generally no best method to implement a successful team. Because top teams in this competition are all long-time participants in the league, the level of play is so advanced that it is generally difficult for new teams to catch up.

The overall level of play increased impressively from RoboCup 2003 to RoboCup 2004, to the great surprise of most of the participants. After ranking eighth in 2003, the STEP team from Russia won this years' competition. It used a kind of playbook that described scenarios and conditions in a rule-based language (Stankevich et al. 2004) to improve the coordination between single agents. For the fifth time since 2000, the Brainstormers team from Germany managed to place among the top three teams in the competition. Brainstormers is known for using reinforcement learning for different behaviors (Riedmiller, Merke, and Withopf 2004). The team has extended the number of behaviors each year, so that now its players are using learned behavior whenever they move in the opponent half. Brainstormers' success with reinforcement learning over the years has inspired a number of other teams to use it, in combination with other techniques, for single skills of players.

Aside from reinforcement learning, behaviors are often hand-coded by various teams. Teams use a number of different approaches for selecting the appropriate behavior, ranging from evolutionary methods (Nakashima et al. 2004) to rule-based systems. An interesting area of research employed by some of the participants is the creation of architectures for agents in a team. Other participants also employ research in methods to aid the construction of

Courtesy, Achim Rettinger.

Figure 9. RoboCup Soccer Simulation League: 3D Simulator.

cooperative agents. Because the data the agents in the 2D competition get are noisy and incomplete, the methods that teams use to maintain a correct and complete world model are also interesting to see. For example, a couple of participants used particle filters (Fox et al. 2001) to improve the self-localization of their players.

The long-discussed step into simulation league 3D has been taken. Some aspects of the 2D simulator are still missing in the new 3D simulator, however. For example, there is no way for agents to communicate with each other. Once the 3D simulator supports this communication, the community will probably discard the 2D simulation league competition. However, because of the existing code bases for teams and the tools created over the years, the 2D simulator will likely remain as an excellent testbed for multiagent research for some time. A long-term challenge for the 3D simulator will be to keep a balance between providing an abstraction of the hardware leagues and being a useful tool for the creation of software smart enough to face the challenge of successfully controlling humanoid robots in a soccer team. A challenge for the community will be to keep the format of the competition so that the results are meaningful and new participants can build upon the research from previous years.

RoboCupRescue Robot League

The goal of the RoboCupRescue Robot League competition is to increase awareness of the challenges involved in urban search and rescue (USAR) applications, provide objective evaluation of robotic implementations in representative environments, and promote collaboration between researchers. The competition requires robots to demonstrate capabilities in mobility, sensory perception, planning, mapping, and practical operator interfaces, while searching for simulated victims in unstructured environments. The arenas constructed to host the competitions are based on the Reference Test Arenas for Urban Search and Rescue Robots developed by the U.S. National Institute of Standards and Technology (NIST) (Jacoff, Weiss, and Messina 2003). The arenas form a continuum of challenges for the robots including physical obstacles (variable flooring, overturned furniture, and problematic rubble) to disrupt mobility, sensory obstacles to confuse robot sensors and perception algorithms, and a maze of walls, doors, and elevated floors to challenge robot navigation and mapping capabilities (figure 10). All combined, these elements encourage development of innovative platforms, robust sensory fusion algorithms, and intuitive operator interfaces to reliably negotiate the arenas and locate victims.

The objective for each robot in the competition is to find simulated victims in unknown locations within the arenas. Each simulated victim is a clothed mannequin emitting body heat and carbon dioxide (to simulate breathing) as well as exhibiting other signs of life including motion (shifting or waving) and sound (moaning, yelling, or tapping). The simulated victims are placed in specific rescue situations (surface, lightly trapped, void, or entombed) and distributed throughout the arenas in roughly the same percentages found in actual earthquake statistics.

The competition rules and scoring metric focus on the basic USAR tasks of identifying live victims, assessing their condition based on perceived signs of life, determining accurate victim locations, and producing human readable maps to enable victim extraction by rescue workers—all without damaging the environment or making false positive identifications.

This year's team qualification process included more than 40 team description papers and regional open competitions in both the United States and Japan. The league chairs and technical committee selected 20 teams from eight countries to compete, almost doubling last year's participation. Overall, the league demonstrated a notable variety of robotic technologies for searching complex environments, finding simulated victims, and localizing and mapping their locations. The overall quality of the implementations was clearly improved from last year's teams. Particularly innovative approaches, documented in team description papers,[2] provided breakthrough improvements in several key elements and will clearly be emulated in the future.

After several rounds of competitive missions, the scoring metric produced three awardees that demonstrated best-in-class approaches in each of three critical capabilities (figure 11).

The first-place award was given to the Toin Pelicans team, from the University of Toin, Japan, which was mainly recognized for its very capable, multitracked mobility platform with independent front and rear flippers. The team achieved an innovative camera perspective by mounting the camera above and behind the robot—thus containing the entire robot and surrounding area within the field of view. This perspective provided superior remote situational awareness for the operator and allowed precise configuration management of the robot's tracks to facilitate mobility over large obstacles and within confined spaces. Other teams used similar overview cameras, some on flexible rods, also to good effect.

The second-place award was presented to the Kurt3D team from the Fraunhofer Institute for Artificial Intelligence Systems, Germany. This team was recognized for its application of state-of-the-art 3D mapping techniques using a tilting line scan ladar within the complex environment of the arenas.

The third-place award went to the ALCOR team, from the University of Rome "La Sapienza," Italy, for its intelligent perception algorithms for victim identification and mapping.

The league's goal was clearly achieved this year by evaluating state-of-the-art technologies, methods, and algorithms applied to search and rescue robots through objective testing in relevant environments, statistically significant repetitions, and comprehensive data collection. Although several teams demonstrated clear advances in certain key capabilities, more collaboration between teams (and between countries) is needed to produce ultimately effective systems for deployment. When viewed as a stepping-stone between the laboratory and the real world, this competition provided an important opportunity to foster such collaborative efforts and further raised expectations for next year's implementations. It also enticed many new researchers into the USAR domain.

This year's competition also featured a focused workshop on Simulation and Robotics to Mitigate Earthquake Disaster, which took place on the team setup day prior to the start of competition and then reconvened after the final awards ceremony. The workshop included 15 paper presentations and more than 50 participants from the existing RoboCupRescue leagues—the simulation league and the real robot league—and others from the autonomous soccer leagues interested in getting involved in this new domain. Two new league initiatives were introduced: (1) a high-fidelity arena/robot

Figure 10. RoboCupRescue 2004 Robot League Arenas.

Figure 11. RoboCupRescue Robot League Awardees in Action.

Top left: Toin Pelicans. *Top right:* Kurt 3D. *Bottom:* ALCOR.

Agent Competition	1. ResQ Freiburg (University of Freiburg, Germany) 2. DAMAS-Rescue (Laval University, Canada) 3. Caspian (Iran University of Science and Technology, Iran)
Infrastructure Competition	ResQ Freiburg (University of Freiburg, Germany)
SICE Technical Award	S.O.S. (Amirkabir University of Technology, Iran)

Table 5. Rescue Simulation League Competition Results

simulation environment to provide a development tool for robot programming in realistic rescue situations, and (2) a common robot platform for teams to use (if they choose to do so) based on a standard kit of components, modular control architecture, and support for the simulation.

Both initiatives received encouraging support and will become integrated into the league during the first RoboCupRescue camp hosted this fall at the fire-rescue training facility in Rome, Italy, which houses last year's RoboCupRescue arenas. This five-day event will provide an educational opportunity for researchers to learn about the state of the art for search robots and a chance to develop modular solutions for five distinct elements: (1) mobility behaviors, (2) perception for victim identification, (3) localization and mapping in complex environments, (4) operator interfaces, and (5) simulation tools. The results of this event will be available to all teams interested in this domain and will be demonstrated during the 2005 competition in Osaka, Japan.

Rescue Simulation League

In the RoboCup 2004 Rescue Simulation League there were two competitions. In addition to the usual agent competition, the infrastructure competition was established in 2004 to promote research. The competition results are given in table 5. A brief description of the competitions follows.

Agent Competition

In the agent competition, each team had a certain number of firefighters, police, and ambulances with centers that coordinated each kind of agent. The bounds on these were determined by the competition rules, whereas the actual numbers were determined by the Technical Committee (TC) and announced just before each run. The agents were assumed to be situated in a city in which a simulated earthquake had just happened, as a result of which some buildings have collapsed, some roads have been blocked, some fires have started, and some people have been trapped or injured under the collapsed buildings. Multiple simulators were used to represent the development of the events and the results of the actions of the agents. The goal of each team was to coordinate and use its agents to minimize human casualties and the damage to the buildings. The rescue domain represented a real multiagent scenario since most of the encountered problems cannot be solved by a single agent. For example, fire brigades depend on police forces to clear blocked roads in order to reach their targets. Similarly, if fires spread out in many directions, they can be extinguished more efficiently by using more than one agent. Moreover, the task was challenging due to the limited communication bandwidth, the agents' limited perception, and the difficulty of predicting how disasters evolve over time. In the competition, even though the overall disaster situation (the locations of agents, fire ignitions, and the magnitudes of earthquakes) for each run was unknown to the teams, the disaster simulator programs and the global information systems (GIS) map data, except the random maps, were provided in advance. The team performance score was calculated using a formula that was based on the number of victims saved and the area of houses that were not burned within the allocated time.

For the 2004 agent competition, there were 34 teams who submitted qualification materials. Among these, 20 teams were selected by the TC. Of the 20 qualified teams, only 17 teams competed. In addition to the three maps used in previous competitions, namely, Kobe, VC, and Foligno, random maps were also used for the first time. The random maps were generated using the Rescuecore tool developed by the Black Sheep team. This year, instead of using configuration files prepared by the teams, as was the previous practice, files prepared by the TC were used. These were prepared so that as the competition progressed, the difficulties of the situations were increased appropriately. The preliminaries consisted of two stages. In the first stage—the traditional competition—the teams competed on six maps with different configurations. The first 6 teams went to the semifinal. The remaining 11 teams competed in the second stage, which was designed to test the robustness of the teams under varying perception conditions. Here the teams were expected to show only slight changes in performance as the conditions deteriorated. The top 2 teams that had the best scores went to the semifinals. Thus 8 teams competed in the semifinals where four maps were used. In the final, the top 4 teams of the semifinals competed.

The winning team in 2004 was ResQ Freiburg. Its platoon agents had reactive and cooperative behaviors, which could be overridden by deliberative high-level decisions of the center agents. Specially developed prediction modules calculated the instantaneous and long-term effects of the actions for evaluation purposes. For the planning of complex sequences of group actions, a new multiagent planning method for abstract search spaces that was generated by agent-specific clustering methods was used. The agents of DAMAS-Rescue, which was the second team by a small margin, were developed with a special agent programming language. The team's Fire Brigade agents chose the best fire to extinguish based on the knowledge they learned with a selective perception learning method. The performance of Caspian, the third team, was also very good.

One of the major problems encountered by the teams was the loss of messages between agents and the simulation system. For the 2005 competition, changes to the simulation environment to solve this problem are being planned.

Infrastructure Competition

The environment rescue agents act in a large-scale simulation, which is both highly dynamic and only partially observable by a single agent. Real disaster situations can rarely be predicted and are often not adequately dealt with when they actually occur. Therefore, it is one of the main goals of the RoboCup Rescue Simulation League to develop realistic disaster simulators that allow agents to develop realistic mission plans. The infrastructure competition tests the performance of the simulator components developed by the teams. The awarded team is requested to provide the component for the next year's competition. For this reason teams are expected to accept the open source policy before entering the competition. Teams present their tools in front of all teams during RoboCup, and ranking is decided with votes from TC members and teams in both agent and infrastructure competitions.

In 2004, only two teams qualified, and only the ResQ Freiburg team competed. It presented a 3D viewer and a fire simulator. Both components were chosen to be used in 2005 if they are ready on time. The 3D viewer is capable of visualizing the rescue system both online and offline. The fire simulator is based on a realistic physical model of heat development and heat transport in urban fires. Three different ways of heat transport (radiation, convection, direct transport) and the influence of wind can be simulated. The protective effects of spraying water on buildings without fire were also simulated (Nuessle, Kleiner, and Brenner 2004).

RoboCupJunior

RoboCup is an extraordinarily long-term research initiative and its 2050 goal is far beyond the end of the professional careers of its initiators and most currently active researchers. Enticing young students to become interested in RoboCup is therefore a very important activity and the task of the educational division of RoboCup—RoboCupJunior.

The idea of RoboCupJunior was pioneered by Lund and Pagliarini (Lund and Pagliarini 1999). They developed a version of robot soccer that uses an infrared-emitting ball and a field covered with a grayscale floor. This setup simplified the tasks of detecting the ball and localizing on the field so that robots built from widely available robot construction kits could successfully play the soccer game. In 2000 and 2001, respectively, two additional challenges were introduced, in which students build and program robots performing on a stage or executing search and rescue tasks.

The use of robotics and robotic technologies in an educational setting has proven to be a very effective way to heighten interest in science and technology among students. As research on the learning effects of preparing and participating in RoboCupJunior has shown (Sklar, Eguchi, and Johnson 2003), students especially improve their individual and social skills (building self-confidence, developing a goal-oriented, systematic work style, improving their presentation and communication abilities, exercising teamwork, resolving conflicts among team members). RoboCupJunior

Figure 12. View of the RoboCupJunior Area.

has spread to more than 20 countries around the world. We estimate that in 2005 more than 2,000 teams worldwide adopted the RoboCupJunior challenges and prepared for participation in RoboCup in local, regional, or national competitions. The largest RoboCupJunior communities are China (approximately 1,000 teams), Australia (approximately 500 teams), Germany, Japan, and Portugal (more than 100 teams each).

In 2004, RoboCupJunior organized its fifth international championships (figure 12). Because of the large number of potential participants, teams in many countries had to qualify for the international championships in national team selection events in order to bring down the number of participants to a manageable number. Nevertheless, with 163 highly competitive teams from 17 countries, 677 participants, and about 300 robots, RoboCupJunior enjoyed a 120 percent increase in the number of teams and 162 percent increase in the number of participants and celebrated its highest level of participation ever.

The Lisbon RoboCupJunior event featured competitions in eight leagues, covering four different challenges—RoboDance, RoboRescue, RoboSoccer One-on-One, and RoboSoccer Two-on-Two—and in each challenge two age groups—primary for students aged under 15, and secondary for students 15 and older. Due to the limited space available for the RoboCupJunior team area, a different and longer overall schedule was adopted this year. The event duration was five days. The first day was reserved for team registration and a series of meetings, at which we instructed referees, coaches, and participants about the latest version of the rules to ensure consistent refereeing and a smooth tournament. Three days were re-

RoboDance	Number of teams	Number of students	Number of females	Percent female	Number of dances
Primary	20	96	49	51	29
Secondary	22	98	30	31	29
RoboRescue	**Number of teams**	**Number of students**	**Number of females**	**Percent female**	**Number of matches**
Primary	20	74	16	22	58
Secondary	18	58	11	19	54
RoboSoccer	**Number of teams**	**Number of students**	**Number of females**	**Percent female**	**Number of matches**
One-on-One Primary	18	73	10	14	53
One-on-One Secondary	16	55	5	9	43
Two-on-Two Primary	19	83	13	15	59
Two-on-Two Secondary	30	140	12	9	76
Total	163	677	146	22	401

Table 6. RoboCup Junior Statistics on Participation and Events.

served for preliminary rounds. Scheduling ensured that each team had all its games on a single day. In all leagues, teams had to have their robots checked for compatibility with the rules prior to participating in any game or event. Furthermore, at least the teams qualifying for the playoffs were interviewed in order to scrutinize their ability to explain their robot designs and programs. On the other two days, teams were encouraged to watch and learn more about the senior RoboCup leagues and to visit a few of the many Lisbon sights to learn about Portuguese culture. The event culminated on its last day, when we had all playoff games, finals, the RoboCupJunior Award Ceremony, and a marvelous and remarkable Junior Party at the Lisbon Oceanarium.

Table 6 summarizes a few statistics on the 2004 RoboCupJunior event. With more than 400 dances, runs, or soccer games overall and about 100 every day, the event had a dense schedule and plenty of activities for spectators to watch. Remarkable is the almost fivefold increase in participation of female students, which was up to 22 percent of overall participants (last year 15 percent).

RoboCupJunior Rescue

The RoboRescue challenge was designed to be an entry-level challenge students could manage even after a few weeks of work with robots. The challenge is performed in an environment mimicking an urban search and rescue site. Robots have to follow a curved path, marked by a black line, through several rooms with obstacles and varying lighting conditions. On their path, they must avoid falling off while mastering a steep slope to the final room. The task is to find two kinds of victims on the path, marked by green and silver icons. Points are awarded for successful navigation of rooms and for detecting and signaling victims, and the time for executing the task is recorded when it is completed. This year, RoboRescue saw a tremendously increased interest with 20 and 18 teams in primary and secondary, respectively. With around 20 percent, female participation is almost at the overall average. On each day, about one third of the teams competed and had to perform two runs through the environment. The best 3 teams advanced to the finals, where 9 teams competed in each age group. Somewhat to our surprise, the vast majority of teams demonstrated perfect runs and quickly navigated through the environment while finding and signaling all victims, so that the timing was the decisive factor for making it to the finals and winning.

RoboCupJunior Soccer

The RoboSoccer leagues play soccer on a table that is covered by a large grayscale floor and surrounded by a black wall. The only difference is that the One-on-One field is smaller. Goals can be detected by the gray coloring of the goal's interior wall. The familiar infrared-emitting ball is used for play. With 83 teams, more than half of all teams, and more than the total of last year, participated in RoboSoccer. For the first time, we had competing in Secondary Two-on-Two 2 teams that were based on international cooperation between schools in Germany, Portugal, and the United Kingdom. Participation of female students is below average in this challenge, particularly in the secondary leagues. Although a detailed statistical analysis is not available, registration records indicate that this is probably related to the different levels of acceptance of soccer as a "girl's sport" in various countries (well accepted in Americas and Asia, less common in Europe). The distribution of teams across leagues was more even this year, which is most likely due to moving the age limit for primary leagues from 12 to 14. On four days of tough competition, participants, coaches, and referees went through 231 games, which produced an average of 15 goals per match and 3,497 goals overall. Match results like 23-22 and 36-19 meant plenty of cheers, as teams celebrated every single goal and made the RoboCupJunior area a beehive of activity. Even seasoned RoboCupJunior organizers were stunned by the sophisticated robots and the spectacular level of play the teams demonstrated across all of the four Junior soccer leagues.

RoboCupJunior Dance

The RoboDance challenge asks students to create a stage performance that involves robots. Students may themselves be a part of the performance, or they may give a narrative to the audience while the robots perform on stage. There is a two-minute time limit for the performance, and an international judge committee assesses the performance in seven categories, awarding points on a scale from 0 to 10. RoboDance is without doubt the RoboCupJunior activity that allows the greatest flexibility in robot design and programming, and it challenges the students' inspiration and creativity. Each year the audience is again surprised and delighted by the students' creative designs and carefully choreographed performances. This year, there were 42 teams with 194 participants. Female participation in this league is well above average and has reached 51 percent in the RoboDance primary league and 31 percent of participants in the RoboDance Secondary league. In both RoboDance leagues, teams were assigned to one of three groups. All teams in the same group performed on stage on one of the three days of preliminaries; the best 3 teams advanced to finals of that league. The two rounds of dance performances on finals day yielded spectacular performances and drew large audiences. It was quite difficult for the judges to select the best teams.

The award winners of this year's competition are listed by league in table 7. Detailed results of the RoboDance, RoboRescue, and RoboSoccer competitions can be found online.[3]

RoboCupJunior Future Challenges

Although RoboCupJunior was significantly larger and longer this year, it ran quite smoothly thanks to the help of many committed teachers, team coaches, parents, and local volunteers, who refereed all events and contributed wherever and whenever help was needed. However, growing interest in RoboCupJunior raises issues about how it should evolve in the future. Plans for the future were discussed in meetings with the national representatives of RoboCupJunior and the technical committees for the leagues. In RoboSoccer, getting rid of the grayscale floor (which has been difficult to produce at reasonable prices in satisfying quality so that sensors of all robot kits used can get good readings), would significantly ease work in schools as well as organization of tournaments. It seems that a majority of teams are not using grayscale any more and instead rely on the magnetic orientation sensors available for most kits. Organizationally, we would like to stimulate exchange and cooperation between teams from different countries. A different tournament format has been suggested and will most likely be applied in the future. In RoboDance, some teams used a very large stage area or expected a particular kind of floor. Rule changes imposing some reasonable limit on available stage area and providing specifications of floor properties are most likely. To stimulate cooperation between teams, we may encourage teams to build ad hoc cooperation and demonstrate their joint team performances to the audience on the last day. In RoboRescue, we want to carefully increase the complexity and difficulty of the rescue arena with the help of experts from the senior rescue leagues.

Wireless Communications

One major drawback noted at RoboCup 2004 was the difficulty with wireless communication. This problem was experienced across all the robot leagues in 2004. A study made during the event showed that most of the trouble comes from two main factors:

First, the 3-channel separation used for the IEEE 802.11b/g standards is insufficient. Probes installed in several hall sites detected a signal-to-noise ratio consistently lower than 40 percent for all 14 channels, which resulted in a large number of frame losses and frame retries.

Second, the entire wireless channel spectrum was consistently saturated by other participants who did not even know their laptops had wireless communications active, and also by the public, media devices, mobile phones, and so on. The number of violation events (for example, one team attempting to use the access point of another field or league) per hour was extremely high—especially in the first days and during event hours.

The wireless communications problem resembles the initial assumption of most RoboCup participants and promoters that using colors to distinguish objects would help overcome perception problems, thus allowing the focus to be on other topics of research concerning cooperation and coordination among robots. Reality has demonstrated otherwise, however; color segmentation in real situations is not a solved problem. Similarly, wireless communications are used by most teams in real robot leagues to "simplify" cooperation and coordination through the use of explicit communications. However, actual experience forced teams again to face the hard troubles posed by reality: one must reduce (or even avoid) explicit communications and be robust to their failures. This difficulty opens new research avenues, for example, on implicit communication and robust communication protocols for robots acting in dynamic adversarial environments.

RoboDance Primary		
1	Coronation Quebec 1	Canada
2	The Rock	Germany
3	Peace of the World	Japan
RoboDance Secondary		
1	Kao Yip Dancing Team	China
2	Mokas Team	Portugal
3	Gipsies	Israel
RoboRescue Primary		
1	Chongqing Nanan Shanh	China
2	Dragon Rescue 100 percent	Japan
3	Chongqing Nanan Yifen	China
RoboRescue Secondary		
1	Dunks Team Revolution	Portugal
2	Ren Min	China
3	Across	USA
RoboSoccer One-on-One Primary		
1	Shanghai Road of Tianjin	China
2	Shenzhen Haitao	China
3	Wuhan Yucai	China
RoboSoccer One-on-One Secondary		
1	Liuzhou Kejiguang	China
2	I Vendicatori	Italy
3	TianJin Xin Hua	China
RoboSoccer Two-on-Two Primary		
1	NYPSTC1	Singapore
2	Ultimate	Japan
3	Red and Blue	South Korea
RoboSoccer Two-on-Two Secondary		
1	Kao Yip 1	China
2	Espandana Juniors	Iran
3	Kitakyushu A.I.	Japan

Table 7. RoboCupJunior Award Winners by Category.

Conclusions

Overall, from a scientific standpoint, RoboCup 2004 was a successful event. The technical challenge of holding the competitions under the existing artificial light of the exhibition hall, instead of having special illumination on each field as in the past, was overcome by most teams without significant problems, thus demonstrating the increased perception robustness within the RoboCup community. Another noticeable improvement was the increase in teamwork across most real robot soccer leagues, from passes to dynamic behavior switching, including formation control and cooperative localization. Even in the humanoid league, a pass between biped robots was demonstrated by one of the teams.

RoboCupJunior was also a tremendous success, despite the increased organizational difficulties caused by the doubling in the number of participants over 2003. Because the number of juniors involved has increased, the hope is that RoboCup is making a serious contribution toward the popularization of science and technology learning among a new large generation of youngsters.

The next RoboCup will take place in Osaka, Japan, in July 2005.

Notes

1. www.RoboCup 2004.pt.

2. The papers can be downloaded from http://robotarenas.nist.gov/competitions.htm.

3. http://www.RoboCup 2004.pt/scoresAndStandings/results-RCJ.

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