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RoboCup-2003
New Scientific and Technical Advances

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■ This article reports on the RoboCup-2003 event. RoboCup is no longer just the Soccer World Cup for autonomous robots but has evolved to become a coordinated initiative encompassing four different robotics events: (1) Soccer, (2) Rescue, (3) Junior (focused on education), and (4) a Scientific Symposium. RoboCup-2003 took place from 2 to 11 July 2003 in Padua (Italy); it was colocated with other scientific events in the field of AI and robotics. In this article, in addition to reporting on the results of the games, we highlight the robotics and AI technologies exploited by the teams in the different leagues and describe the most meaningful scientific contributions.

RoboCup is an international scientific initiative that at the moment of writing involves more than 300 research groups active around the world. As the charter of the International RoboCup Federation states, "RoboCup is an international research and education initiative. It is an attempt to foster AI and intelligent robotics research by providing a standard problem where a wide range of technologies can be integrated and examined [...]."

In the early years of RoboCup, the standard problem was the soccer game. Soccer was chosen because of the many challenging issues a robot must face to play the game effectively. For example, it has to react in real time to a highly dynamic environment, cooperate with teammates, be able to distinguish between teammates and opponents, and so on. The ultimate goal of RoboCup was formulated as "building by the year 2050, a team of fully autonomous humanoid robots that shall win a soccer match against the human World Champion under the official regulations of FIFA" (Kitano 1999a).

We do not promise that this goal will be reached by 2050, but the RoboCup initiative has already produced the result of creating interest and disseminating knowledge about AI and robotics, growing from a small meeting for a few interested scientists to the biggest robotics event in the world. In fact, today, RoboCup has evolved, and the soccer games are just one part of the RoboCup activities, which now consist of RoboCup international competitions and conferences; technical conferences (usually colocated with the RoboCup event); RoboCup challenge programs (in which challenges are designed to foster the RoboCup community to be active in different research issues); education programs for primary, secondary, and undergraduate students; and infrastructure development (for example, every year, the training arena built by the Rescue League is kept in the country hosting the RoboCup event as an open facility for research groups active in rescue robotics).

In the rather short history of RoboCup, the number of participating teams has increased so quickly (figure 1) that the organizers now have to put a limit on the number of participating teams in each league. In fact, in recent years, some leagues have introduced qualifications. Nevertheless, the number of teams registered in the competitions has steadily increased year after year. In RoboCup-2003, we reached the limit beyond which the organization of the event and the space requirements became unmanageable: We had a total of 1,244 registered participants and 243 teams coming from about 30

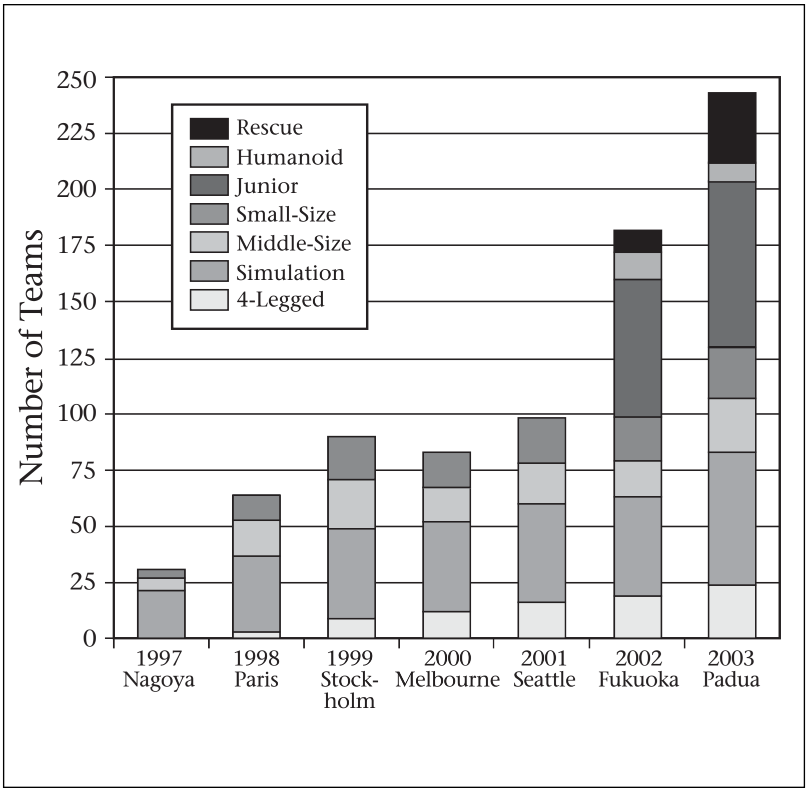
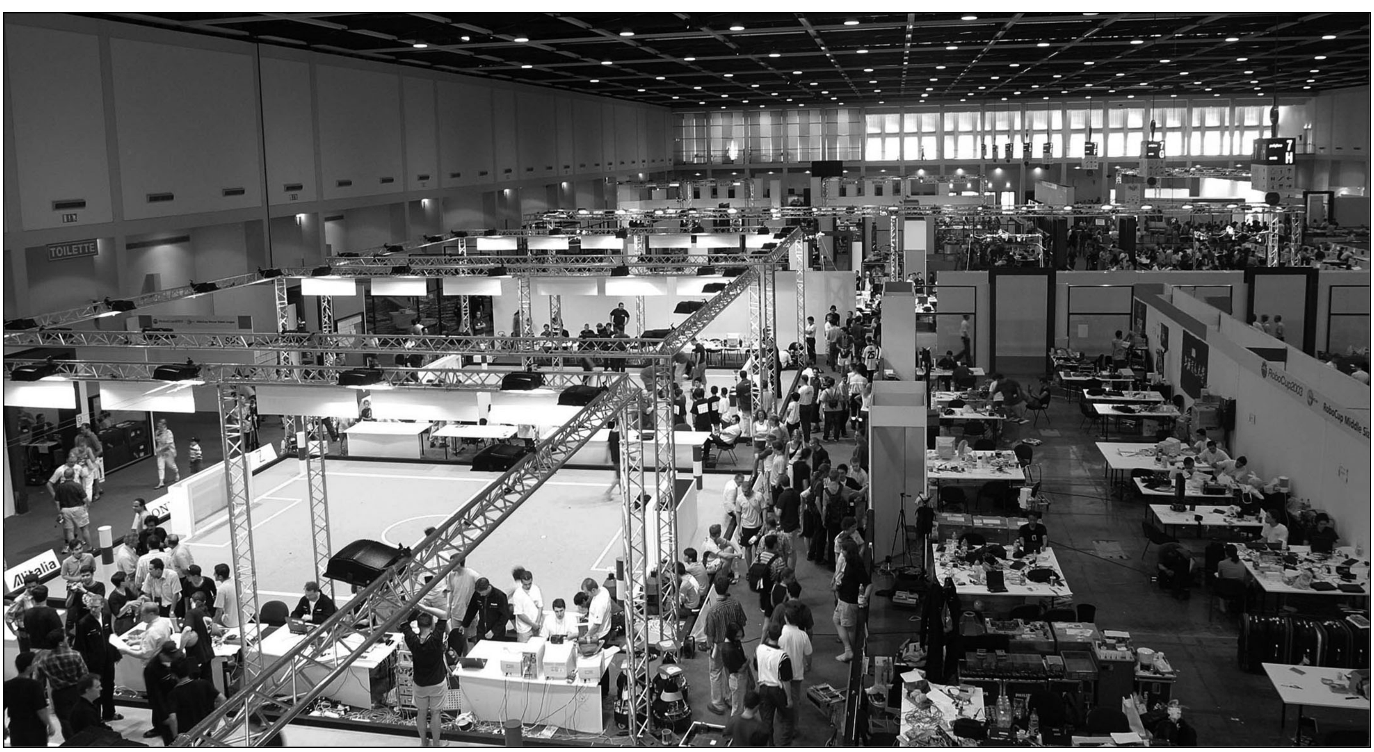


Figure 1. The Number of Teams Participating in the RoboCup Competitions from 1997–2003.

Figure 2 (below). A View of the RoboCup 2003 Fields.



countries from 4 of the 5 continents (table 1).

Every year during the competition and the symposium, new technologies emerge in one or more leagues. In the ensuing years, these new technologies are consolidated and diffuse to other leagues and become more and more important in the larger robotic community outside RoboCup. An example of the scientific and technical advancements achieved by the RoboCup researchers, *RoboCuppers* as they call themselves, is the fact that some of the fundamental problems addressed by Asada et al. (1999) in the very early years of the RoboCup competitions are now solved by most of the teams (for example, real-time perception, reliable hardware platforms, centralized control of a robot team, basic cooperative behavior), and the current team research is focusing on more advanced issues.

One example from past years is omnidirectional vision that proved to be effective in highly dynamic environments such as RoboCup (Bonarini 2000; Marchese and Sorrenti 2001; Marques and Lima 2001; Menegatti et al. 2002: Suzuki and Asada 1998). In 2003, the promising technologies awarded by the symposium were recognition and prediction of situations (Miene, Visser, and Herzog 2004), automatic color camera calibration (Cameron and Barnes 2004), and information processing that overcomes physical sensor limitations (Quinlan et al. 2004).

Other important scientific contributions that go beyond the individual leagues and have a far-reaching effect in the robotics community outside RoboCup are described in the journal special issues explicitly on RoboCup or in the special issue on multirobot systems that has seen significant contributions from the RoboCup community. One for all is the work reported by Weigel et al. (2002). He focuses on multiagent coordination for both action and perception, based on a robust probabilistic tracking technique using laser range finders and a global perception-integration module running in an off-field computer.

A complete overview of the seven-year-long history of RoboCup can be obtained from the collection of books on RoboCup (Asada and Kitano 1999; Asada et al. 2000; Birk, Coradeschi, and Tadokoro 2002; Kaminka, Lima, and Rojas 2003; Kitano 1998b; Stone, Balch, and Kraetzschmar 2001; Veloso et al. 2000) and the annual reviews of the RoboCup event in *AI Magazine* (Asada et al. 2003, 2000; Coradeschi et al. 2000; Noda et al. 1998; Stone et al. 2001; Veloso et al. 2003).

Currently, the competitions of the RoboCup World Cup are divided into three major branches: (1) RoboCup Soccer, (2) RoboCup Rescue, and (3) RoboCup Junior. In RoboCup Soccer, the research of the teams is focused on the final goal of building robotic soccer players; in RoboCup Rescue, the teams apply their research to robotics-assisted urban search and rescue operations; and in RoboCup Junior, robotics is seen as an educational vehicle to interest students in computer science and engineering fields and foster personal growth in areas such as teamwork and communication skills. In every branch, there are several leagues differing in the size and characteristics of the robots used. This article follows this organization, and each section reports on the status and advancement of the different leagues that participated in 2003 in Padua. RoboCup-2003 was organized by the RoboCup Federation and PadovaFiere S.p.A. (the Fair of Padua) inside the pavilion of the Fair of Padua (figure 2).

Symposium

Every year, the RoboCup competitions are held together with the International RoboCup Symposium. In 2003, the symposium was held 10 to 11 July, directly after the competitions.

The symposium attracted 150 to 200 researchers a day. More than 60 researchers not affiliated with teams in the competitions registered specifically to attend the symposium. The number of submissions to the RoboCup symposium increases each year. The RoboCup-2003 symposium received 125 submissions. A total of 31 of the submitted papers were accepted for oral presentations.

Because of the large number of participants and oral presentations, for the first time, the symposium was held in parallel sessions. The presentations were grouped into four sections: (1) AI, (2) artificial vision, (3) humanoid and legged robotics, and (4) miscellaneous robotics. From the titles of the sections in this article, it is easy to understand that the scope of the presented papers stretched beyond the RoboCup competitions to cover general research topics. The RoboCup symposium is the place where the scientific achievements of the teams are discussed and formalized, and the achievements in the RoboCup games are diffused to the scientific community.

The symposium was opened by Manuela Veloso and Masahiro Fujita in the beautiful ancient main hall of the University of Padua (figure 3). It was here that Galileo Galilei taught; the original cathedra of Galileo is preserved, and the family crests of ancient students of the University of Padua are shown. Veloso spoke on the achievements and the progress of RoboCup during its seven-year history, and Fujita gave a demonstration of the impressive capabilities of the new humanoid companion robot developed by Sony.

The other invited talks were given by Ulrich Nehmzow, on the use of dynamic systems methods and chaos theory in the study of robotic environment interaction, and by Paolo Dario, a president of the Robotics and Automation Society of the Institute of Electrical and Electronics Engineers, on the use of robotics in medicine and other fields. We also had a video contribution on multirobot cooperation from Maja Mataric, who was not able to attend the symposium.

Every year, the RoboCup Symposium Committee awards two prizes: (1) the RoboCup Scientific Challenge Award and (2) the RoboCup Engineering Challenge

Country	Teams
Japan	42
Iran	37
Germany	35
USA	18
Australia	15
China	14
Italy	14
Canada	9
Portugal	9
Singapore	9
Netherlands	5
Sweden	5
United Kingdom	5
Russia	4
Slovakia	4
Taiwan	3
Austria	2
Turkey	2
Chile	1
Finland	1
Latvia	1
Malaysia	1
Mexico	1
New Zealand	1
Norway	1
Poland	1
Romania	1
Spain	1
Thailand	1
Total	243

Table 1. Participating Teams by Country of Origin.

Figure 3. The Opening Invited Talk, Held in the Ancient Main Hall of the University of Padua.

Award. The Scientific Challenge Award was won by Andrea Miene, Ubbo Visser, and Otthein Herzong for a method that recognizes and predicts game situations. The Engineering Challenge Award was given ex aequo to Daniel Cameron and Nick Barnes for an autonomous mechanism for color calibration and to Michael J. Quinlan, Craig L. Murch, Richard H. Middleton, and Stephan K. Chalup for an example of how the limitation of a physical sensor can be overcome by appropriate information processing.

The RoboCup-2003 symposium ended with the RoboCup road map discussion. The RoboCup road map is aimed at identifying the intermediate milestones to be reached to achieve the ultimate goal of 2050. The discussion considered the milestones to be reached in the different leagues and also the synergies, the interactions, and possibly the merging of the different leagues.

Scientific Collateral Events

RoboCup-2003 was colocated with several scientific events. We had a one-day workshop entitled Synthetic Simulation and Robotics to Mitigate Earthquake Disaster, chaired by Daniele Nardi; a one-day conference entitled Multirobot Systems: Trends and Industrial Applications, organized by SIRI (the Italian Association for Robotics and Automation) and chaired by Giuseppina Gini and Rezia Molfino; and the three-day Japan-Italy bilateral seminar of the Japanese Society for the Promotion of Science (JSPS) and CNR (National Research Council of Italy), chaired by Minoru Asada and Enrico Pagello. The JSPS-CNR Bilateral Seminar was an exciting event, highlighting the scientific cooperation between Italy and Japan; it involved a tight schedule with many talks and panel discussions. In the end, the technical discussion between scientists of the two countries concluded with the agreement to commence work on cooperative projects in two areas that have been identified as some of the most important application areas for AI and robotics technologies, namely, (1) rescue robotics and (2) simulation environments for mobile robots.

RoboCup Soccer

RoboCup Soccer is the oldest RoboCup activity and the one directly involved in the achievement of the ultimate goal. It is divided into five

Figure 4. The LCD and Projector Displays on Which the Games of the Simulation League Are Displayed.

leagues, each one dealing with a different set of research issues. In the Soccer Simulation League, researchers work on multiagent coordination and high-level strategies without having to bother with hardware limitations. In the Small-Size League, the research focuses on the centralized control of many small robots. In the Four-Legged League, the focus is on the development of software for autonomous robots able to process local sensory information and cooperate with other robots, without the troubles of customized hardware because a stable, reliable, and standardized platform is used (Sony AIBO robot). In the Middle-Size League, the researchers have to build, maintain, and program a team of fully autonomous wheeled robots. In this league, the robot has to move at high speed (often more than 2 meters a second) on a large field (10 meters by 7 meters), carrying its own sensors and its own power supply. It must be able to cooperate with its teammates and sense the environment effectively (recognizing the objects in the field of play and discarding objects outside the field, such as the audience or human team members). Finally, in 2002, the Humanoid League was introduced. Here, humanoid robots, although not yet performing full soccer matches, demonstrate different abilities through a series of technical challenges.

Beginning a couple of years ago, the different leagues introduced challenge competitions in addition to soccer games. These challenges push the teams to improve their abilities for future competitions and advance the technology, for example, to be less dependent on color information, have more reliable sensing, and develop cooperative behaviors.

Simulation League

In contrast to the real robot leagues, many of the challenging features of the simulation league are hidden to the casual observer. Nevertheless, the league has made big progress in the last several years in both game quality (it looks similar to real soccer games) and the scientific methods behind the teams.

The purpose of the Simulation League is to provide a test bed for the development of advanced control architectures and algorithms. Therefore, soccer simulation has to provide a reasonably abstract view relative to a concrete hardware robot (because real platforms change from year to year). However, simulation has to be realistic enough to allow the transfer of developments to the real robot league as a crucial requirement for the final goal in 2050. The Simulation League has many features meeting this specification: 11 independent autonomous software agents to each team, selectable trade-offs between accuracy of sensor information and timing, restricted communication abilities, noise in action and sensing, and heterogeneous players. A successful team in the simulation league has to address all the following issues: decentralized control of 11 independent and autonomous software agents; action under limited sensor information; coordination with limited communication bandwidth; and resource management of limited power, dealing with different player capabilities.

The big advantages of the Simulation League are that only limited hardware resources are required (two to three PCs are usually enough to reasonably play a game) (figure 4); the robots are unbreakable; and each game can be logged and replayed exactly with all state information available. Thus, algorithm development is quite effective and enables the teams to concentrate on sophisticated abilities in both individual robot capabilities and team coordination issues.

Therefore, the Simulation League is the most advanced with respect to team coordination. In the Simulation League, the ability to play reasonable passes is a crucial requirement to be competitive. Also, the restricted energy resources (*stamina*) require a careful distribution of tasks in both defense and attack.

The 2003 tournament again showed a big advance in the performance of the teams. For the first time, all games were started automatically, which resulted in a very smooth time schedule and forced the developers to provide more autonomy to their teams (for example, by effectively using the coach). Of 56 teams that qualified, 46 teams participated in the tournament. In the first round, all participating teams showed a good level of individual skills. The teams that advanced to the second round additionally showed a good level of team play abilities. The 12 finalists that entered the third round all showed a high level of team play and basic capabilities, including very precise knowledge of their own and other player's positions and intentions. Exciting games happened among these teams. Unlike previous years, games were often not decided until the end, with both teams scoring goals.

The top teams all showed mature capabilities in team play, stamina management, active vision, the use of heterogeneous players, and communication. The main reason for the success of the winning teams is a highly elaborate software design that considers all these issues. Different techniques are used for different aspects of the overall problem. Methods are taken from mathematical optimization theory; machine learning; evolutionary algorithms; and also classical AI techniques, such as heuristic search. However, there is no single technique that can be judged to be the most successful; rather, it is a carefully balanced application of useful approaches of various fields. For example, the winning team, UVA TRILEARN (The Netherlands), used coordination graphs to specify multiagent decision making (Menegatti and Pagello 2004). It applied coordination graphs to the continuous domain by assigning roles to the agents and then coordinating the different roles. Furthermore, it used a method to predict the optimal action of the other agents, making communication unnecessary. The second-place team, TSINGHUAELOUS (China), used reinforcement learning for a kicking procedure (Menegatti and Pagello 2004), gradient-based POMDP (partially observable Markovian decision process) learning for ball handling, a coordination scheme for defense based on a global plan, and methods for adaptive communication. The third place team, BRAINSTORMERS (Germany), worked for several years on machine learning methods for the soccer domain and realized a growing part of basic skills (kicking, positioning, intercepting) and tactical multiagent coordination issues (attack play) by neural network–based reinforcement learning methods (Menegatti and Pagello 2004), partially combined with constraint-based search methods.

The coach competition aims at measuring the usefulness of an additional observing and advice-giving agent, the *coach*. By sending messages to a team, the coach can influence strategic behavior such as being more defensive or going by way of the wings. The winner of the coach competition was University of Texas at Austin VILLA, with a coach that learned from analyzing previous games, followed by FC PORTUGAL (Portugal) and the team IRANIANS (Iran).

In the visualization competition, teams compete for the best visualization or game analysis system. In 2003, many interesting contributions were presented (three-dimensional [3D] monitors, graphic game analysis tools), most of which are freely available. The competition was decided by voting. In 2003, the competition was won by the CASPIAN team (Iran), followed by the IRANIANS (Iran), and team AVAN (Iran).

Currently, a new simulator is being developed. Its main features are a 3D world representation and the ability to simulate a broad range of robotic actuators and sensors. Its first release is scheduled for January 2004, and the first competitions using this simulator will take part during RoboCup-2004 in Portugal. It will be another major step toward bridging the gap between simulation and reality.[1]

Small-Size League

The Small-Size League competition hosted 20 teams from all over the world. Each team demonstrated 5 robots on a field that was 2.8 meters by 2.3 meters (figure 5). The official ball was an orange golf ball. Teams were allowed to

Figure 5. A Phase of the Game in the Small-Size League.

use one or more global cameras, so the vision problem was easier to solve, allowing most teams to focus their research on team dynamics and coordination. All teams used one or two cameras placed three meters above the field to extract the position of the ball and robots. Both the image processing and the high-level decisions were typically performed on an external computer, and the low-level commands were sent to each robot over a radio link. Team performance was very dependent on the quality of that radio link. Fortunately, because of the experiences of most teams and a carefully chosen schedule, there were very few problems.

The major advance in 2003 was the implementation of full-team autonomy from human commands, which was possible because of the introduction of the referee box. All the in-game commands, sent from the referee to the teams, were sent directly to the software that controls each team, resulting in no human intervention during the games, which greatly improved the flow. There was a certain convergence on the robot design because most teams adopted an optimized solution. Almost all teams used three or four omnidirectional wheels to each robot. The additional maneuverability of these robots made the two-wheel configuration almost obsolete in this league. Most top teams focused on having an efficient dribbler and kicker. The dribbler devices were typically a set of rotating rubber cylinders that transmit a backspin to the ball, keeping it almost glued to the robot even when traveling on the field. It was a general concern that this feature was overused, and some kind of limitation should be imposed for the 2004 competitions.

The three top teams were, respectively, (1) BIGRED'03, Cornell University; (2) ROBOROOS, The University of Queensland, Australia; and (3) FU FIGHTERS, Freie Universitaet Berlin, Germany. These teams were very evenly matched, and all the games between them were decided by only one goal. The champions, the BIGRED'03 team, showed excellent robot and ball control, which allowed them to score the decisive goals. The ROBOROOS team had the best overall ball control, and its dribbler was able to rob the ball from almost any opponent. The FU FIGHTERS robots showed their famous speed and teamwork, which allowed them to score more goals than any other team in the competition.

Figure 6. A Phase of a Game in the Four-Legged League.

In general, both the team members and the public found the 2003 games to be fast, exciting, competitive, and much more fun to watch than previous years.[2]

Four-Legged League

The distinguishing feature of the Four-Legged League has been that all teams use a common hardware platform, the Sony AIBO robot (figure 6). Because the platform is fixed, the teams are freed from hardware design concerns and are able to concentrate on software development. The common platform also means that teams are easily able to share programs. These features have allowed the league to progress rapidly because new teams can quickly become competent by using previous code as examples for their own development, and experienced teams are able to understand, in detail, how other competitors have solved similar problems.

Games in this league are played by two teams of four robots each, on a field almost three meters by five meters surrounded by a white edge, colored goals, and six color-coded landmarks. All sensing and processing must be done on board the robots. Radio communication between robots is allowed, but bandwidth is limited to 2 million bits a second. Radio communication is also used by the referee to send the robots start, stop, and penalty signals from a referee box.

In RoboCup-2003, 24 teams from 17 countries participated in this Four-Legged Robot League: 8 from the United States, 5 from Asia, and 4 from Australia. The rUNSWIFT team, from Australia, earned the first-place award in the 2003 tournament. This team was champion in 2000 and 2001 and placed second in 2002. UPENNALIZERS (United States) placed second, and NUBOTS (Australia) placed third. In the Four-Legged League, two different philosophies of robot programming are measuring themselves, that is, (1) hand-coded robot programs and (2) learned behaviors and controls. The winning team, rUNSWIFT, used machine learning techniques to optimize the speed of the walking gait (particularly useful when playing on different fields with different carpet and foam backing) and reinforcement learning for path planning and obstacle avoidance. Although the NUBOTS team obtained a winning strategy by carefully hand-coding elementary behaviors and locomotion, one of the strong points of UPENNALISERS was the implementation of an efficient Rao-Blackwellized particle filter for robot localization.

The quality of the games has grown very rapidly during the short lifetime of this league. In the first years, most of the research effort was focused on achieving reliable low-level functions: locomotion, ball control, perception, and self-localization. Typically, a team with better locomotion and simple strategy would outperform a team with sophisticated strategy but slow or imprecise motion. Today, most teams feature fast and stable walking, accurate ball control, reliable ball perception, and good self-localization. A major factor in this progress is the code-sharing policy adopted within the league. A drawback of this policy is a potential reduction in diversity because many teams prefer to improve on existing successful techniques rather than try to invent radically new ones.

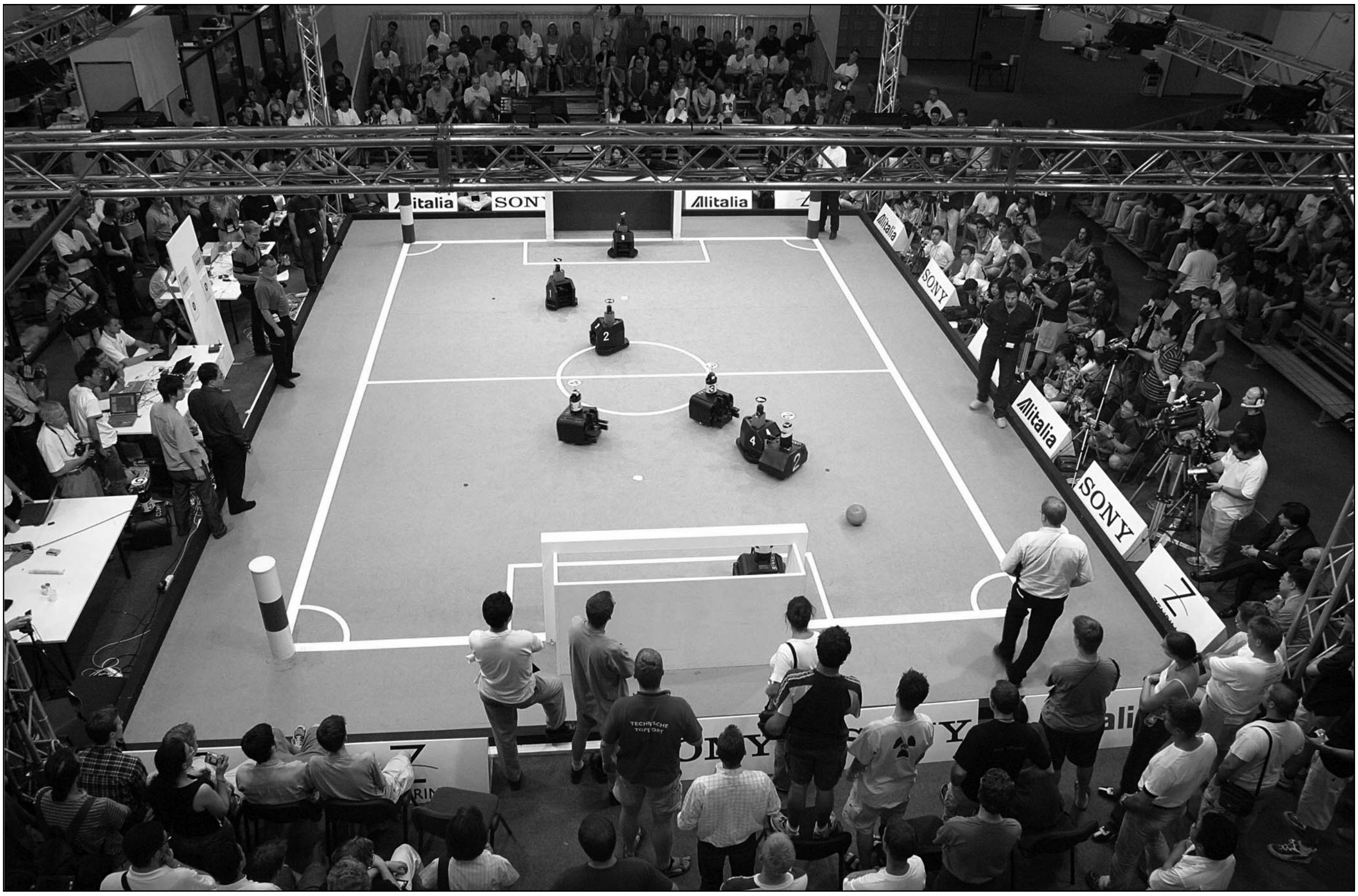


Figure 7. The Final Game of the Middle-Size League.

The WinKit team is defending the blue goal; the FUSION team is defending the yellow goal.

The league is experiencing a shift in the research focus from lower-level functions to higher-level skills such as planning, coordination, and adaptation. Most teams in 2003 used some form of multirobot cooperation, including dynamic role assignment and information sharing. Much more development in this respect is expected in the next years. For example, still very little passing occurs between players, and learning has only been used to improve perception and motion abilities.

In addition to the games, the Four-Legged League organizes a few technical challenges every year. These are meant as test beds for major planned changes to push the teams to prepare for these changes and verify if the league is ready for them. In 2003, the three challenges were to (1) use a black-and-white soccer ball instead of the current orange one, (2) self-localize without the help of artificial beacons, and (3) perform reliable collision avoidance. The top teams in the combined ranking were, respectively, the German team (Germany), RUNSWIFT (Australia), and ARAIBO (Japan).

The last challenge showed that most teams are able to perform vision-based collision avoidance, even if reliability is limited by the lack of proximity sensors around the body of the AIBO. The first and second challenges, however, indicated that the league is not yet ready to eliminate the colored landmarks that simplify the perception problem. Going toward less artificial environments and more natural lighting conditions is one of the next steps in the evolution of our league.[3]

Middle-Size League

The RoboCup-2003 Middle-Size League attracted 24 teams from 11 countries to participate in the robot soccer tournament.

In this league, the field of play is moving fast toward a real soccer field. In 2002, the walls surrounding the field were removed and substituted with a fence of poles half a meter tall. In 2003, the poles were removed, keeping only a security bar around the field to prevent robots from leaving the field. The field was also enlarged to 10 meters by 7 meters. The tournament was played concurrently on four such fields.

Figure 8. Honda Humanoid FIRSTSTEP Kicking a Penalty against a Human Goalkeeper.

Nearly all the participating teams accommodated this change in field set up without problems, demonstrating the robustness of their robot vision systems, which were able to distinguish between objects on the field of play and objects outside the field of play.

The development of the robots shows a clear trend toward omnidirectional drives, omnidirectional vision systems, and increased robot speed. Particularly new teams such as BRAINSTORMERS TRIBOTS (Germany), MOSTLY HARMLESS (Austria), and PERSIA (Iran) came up with new platforms using this kind of drive and sensor concept.

This year's winner of the Middle-Size League tournament was the FUSION team from Japan, which played an exciting final match against WINKIT, also from Japan (figure 7). As in the previous year, two Japanese teams reached the final. This year's third-place team was PERSIA (Iran), which beat last year's champion, EIGEN (Japan), in their final match. The winning FUSION (Japan) team showed a remarkable ability to control the motion of the robot, especially when dribbling the ball. A key point for this skill was definitely good integration and fine tuning of motion control with the physical ball-control device. The robots were able to drive curves without losing the ball, so they were able to effectively dribble around opponents.

The challenge competition consisted of two events. In the first challenge, the robot had to demonstrate ball dribbling through randomly positioned, static obstacles and score once past mid-field. The second challenge was a free challenge. Every team had as many as five minutes of oral presentation and a short demonstration of innovative capabilities. Some teams demonstrated cooperative behaviors or the ability to play with a standard Fédération Internationale de Football Association (FIFA) ball. Other teams gave insights into their ongoing research, including, for example, studies on new ball-stopping mechanisms, continuous passing or other soccer-playing behaviors that had been evolved in a physical robot simulator. The challenge winner was the team ATTEMPTO! TUBINGEN from Germany.

Vision is a major research topic of all middle-size teams. Teams rely on commercial libraries only if they use dedicated hardware for vision processing. All teams use color information, but only one half of them use shape detection and even less edge detection. A few teams use existing software libraries such as CMVISION, OPENCV, or commercial products. Only four teams perform research on color autocalibration. However, this will be a hot research topic of major importance, when lightning conditions will be relaxed next year.

The teams' solution to the self-localization problem was mainly based on visual landmarks. Most teams only used the bigger landmarks such as the goals and the corner posts, but one half of the teams also detected the lines on the field. Meanwhile, only half of the teams used statistical approaches for self-localization, that is, Monte Carlo and particle filters.

One half of the teams used reactive control architectures adapted from Brooks's behavior-based robotics, that is, subsumption architecture or motor schema. One-third of the teams used their own architectures such as dual dynamics, inference machines, hybrid control system, two-level finite-state machines (FSMs), or fuzzy approaches. One-third of the teams developed robot skills using learning approaches. Less than one half of the teams extended reactive motion control methods with path planners, which in the majority of cases were based on potential field methods.

In the 2004 competition, the Middle-Size fields will be even bigger, increasing to 12 meters by 8 meters, allowing teams to have more than 4 robots playing in the field. In addition, the lighting conditions will be less standardized, with the teams playing in indoor ambient light. These changes to the league are meant to foster team play and incrementally migrate to more natural lighting conditions. By 2004, a referee box will be available, allowing the robots to react to referee decisions such as fouls, throw-ins, and corner kicks, which will reduce manual interactions and game interruptions, moving one incremental step toward the vision of playing successfully against humans by the year 2050.[4]

Humanoid League

The Humanoid League has different challenges than other leagues. The main difference is that the dynamic stability of robots needs to be well maintained while the robots are walking, running, kicking, and performing other tasks. Furthermore, the humanoid soccer robot has to coordinate perceptions and biped locomotion and be robust enough to deal with challenges from other players.

The Humanoid League is still rapidly developing. Test games could be performed. However, the competition consisted of four nongame tasks, including standing on one leg, walking, kicking a penalty, and doing free style.

Team	Time
HITS-Dream	40 s
Senchans	256 s
Foot-Prints	268 s
Robo Erectus	346 s
(Real Human	< 15 s)

Table 2. Results from the Walking Competition.

The task was to go to a pole, go around it, and return to the starting position. The distance between the starting position and the pole was five times the height of the robot.

A number of excellent robots were presented in the competition. After a good competition with tight results, Honda International Technical School's HITS-DREAM received the Best Humanoid Award (figure 8). Second place was awarded to the SENCHANS team from Osaka University.

Humanoid soccer robots are complex machines, which should have advanced abilities from very different fields of technology. In this article, we look at seven levels: (1) materials, (2) locomotion, (3) manipulation, (4) power, (5) communication, (6) perception, and (7) intelligence. The task of humanoid robot soccer is rather hard. However, advances in each field are emerging quickly. Thus, it seems feasible to achieve the following developments by 2010:

Materials: Artificial muscle, softer surfaces for robots

Walk: Dynamic walk, jump, and run

Kick: Kick moving ball, pass

Manipulation: Humanlike gripping

Power: Six-hour rechargeable batteries

Communication: Body and natural language processing

Perception: Navigation in human environments

Intelligence: Task understanding

For the next years, dynamic walking is surely the most interesting challenge in the humanoid league (cf. table 2). The best industrial robot is still significantly slower than the average human.

In addition, it is noted that integration is one of the biggest challenges in the field of humanoid robotics. Although it is not that difficult to build a vision system or control mobility, it is hard to do all these things at the same time, on the same robot, with both high reliability and secure recovery procedures in the case of a subsystem failure.

A road map for the next few years could be the following:

2004: More challenges in the free-style competition, for example, balancing, passing, and obstacle walking

2005: One versus one game, fully autonomous robots

2006: Two versus two game, challenges on multiple-object tracking and collision avoidance

The rules for 2004 are still being discussed.[5]

RoboCup Rescue

Robotic-based urban search and rescue (figure 9) was chosen as an important domain for RoboCup because it is socially relevant and shares several key technical challenges with soccer. For example, some of these commonalities include "long-term strategy planning, logistics, [and] interaction with human agents." RoboCup Rescue brings these issues into focus by trying "to investigate the essence of autonomous multi-agent systems through the use of an additional domain similar to soccer" (Asada and Kitano 1999). When these words were written, RoboCupRescue was an infant project. After three years of development and competitions, we can say that many technologies have been applied from RoboCup Soccer to RoboCup Rescue; for example, this year, a fully autonomous robot almost directly from the Middle-Size League competed in the Rescue Robot League, and behavior prediction techniques used in Soccer Simulation League were also used to predict changes in the disaster environment of the Rescue Simulation League games.

Simulation League

The RoboCup-2003 Rescue Simulation League tournament hosted 17 teams, many competing for the first time. After RoboCup-2002, useful tools such as JAVA-based agent developing kits, JGISEDIT, and a multiplatform map editor with a map of the city of Foligno, Italy, helped new teams to join the RoboCup Rescue community.

In rescue simulation games, a team has specific resources available: a certain number of fire fighters, police, and ambulances. These agents are inserted into a virtual city in which a simulated disaster happens, namely, an earthquake, which causes fire ignition, collapsed buildings, and injured people. The goal of the team is to coordinate and exploit their resources to minimize human casualties and damage to the buildings. The team performance is scored based on the number of victims saved and the time it takes to successfully complete the rescue operations.

Even though the overall disaster situation is unknown to the rescue teams (the locations of agents, fire ignitions, and the magnitudes of earthquakes), the global information systems (GIS) map data and the disaster simulator programs are provided in advance. Apparently, this a priori knowledge simplifies the rescue simulation task compared to the Soccer Simulation League. In fact, the factors that change the citywide disaster environment are easier to predict than the behavior of an opponent team in soccer games. For example, a Rescue Simulation team with an understanding of what particular features are seen across a simulated city and how they can become overloaded with traffic during a disaster has a notable advantage in planning and executing operations. However, dealing efficiently with a myriad of possible reactions to events is very important in real disasters and is one of the important applications of AI and computer science.

This year, the map of Foligno, Italy (figure 10), was adopted as an official map for the competition. Simulating a disaster in this city illustrated the importance of RoboCup Rescue to the audience and especially to the Italian audience. An earthquake seriously damaged the city of Foligno just a few years ago. The Foligno map was twice the size of the two previously used maps—Kobe, Japan, and the so-called Virtual City—and provided ample challenges for the teams competing in RoboCup-2003. In the preliminary games, all teams performed rescue operations at two disaster situations in the three different maps.

Compared to the games played in RoboCup-2002, the teams showed increased abilities both in the single autonomous agents (fire fighter, police, and ambulance) and in the cooperative abilities among the agents. To improve the capability of their agents, the teams used online learning methods for rescue formations, clustering methods, or agent group formation mechanisms.

The winning team this year was ARIAN from Iran. One of the key features of its software agents was the capability to predict the future state of the disaster map. Thus, the actions of ARIAN agents at one simulation step were decided not only from past and present states but also from future disaster state. The performances of the second team, YOWAI (Japan), and the third, S.O.S. (Iran), were also very impressive.

For the 2004 competition, new challenges might be introduced: (1) given unfamiliar maps, teams do some operations and compete according to their improvement over multiple games (online learning competition); (2) given all teams a fixed set of rescue agents, the teams build a set of "head office agents," competing in their ability to control the rescue agents; and (3) interact with real rescue robots for decision support and application of intelligent controls.

Also, new map generation and automatic simulation tools will enable opportunities to promote both rescue simulation research and application objectives in the future.[6]

Robot League

RoboCup-2003 hosted the third Rescue Robot League competition, which included 12 teams from 8 countries. The goal of this competition, which is exactly similar to the annual American Association for Artificial Intelligence (AAAI) competition, is to increase international awareness of the challenges involved in urban search and rescue applications, provide objective evaluation of robotic implementations in representative environments, and promote collaboration between researchers. Both competitions require robots to demonstrate capabilities in mobility, sensory perception, planning, mapping, and practical operator interfaces while they search for simulated victims in unstructured environments. The rescue 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).

The objective for each robot in the competition is to find simulated victims at unknown positions in the arenas. Each simulated victim is a clothed mannequin emitting body heat and possibly other signs of life, including motion (shifting or waving), sound (moaning, yelling, or tapping), and carbon dioxide to simulate breathing. The victims are distributed throughout the environment in roughly the same situational percentages found in actual earthquake statistics.

The competition score metric focuses on the tasks of identifying live victims, determining victim condition, providing accurate victim location, and enabling victim recovery, all without damaging the environment. Also, false victim identifications were discouraged for the first time, so teams that mistakenly identified sensor signatures as signs of life suffered point reductions. The 12 competing teams developed unique systems with very diverse characteristics.

The 2003 competition hosted 12 teams that demonstrated robotic systems with very diverse characteristics. The first-place award winner was the ROBRNO team from Brno University of Technology in the Czech Republic. The team developed a very capable custom robot and integrated several components to form an extremely effective operator interface. Their robustly fabricated four-wheel, skid-steered robot was equipped with vision, infrared, and audio sensors for victim identification. The operator interface used a joystick to control robot motion along with heads-up display goggles that tracked the orientation of the operator's head to automatically point the robot's cameras. Thus, superior remote situational awareness was allowed, and the operator was able to intuitively and dexterously negotiate narrow arena

Figure 9. A Robot Found a Victim in the Rescue Robot League, and Two Referees Update the Score.

Figure 10. A Phase of the Games of the Simulated Rescue League.
The LCD displays show the disaster map in the city of Foligno, Italy.

passages, causing very few penalties. The second-place award winner was the CEDRA team from Sharif University of Technology in Iran. It developed a wheeled mobility platform with an articulated body design similar to planetary explorers. It also used a joystick interface, with the operator looking at two flat-panel video displays. The third-place award winner was the MICROROBOT team from the Isfahan University of Technology in Iran. It used two robots equipped differently and used cooperatively. One robot was small and fast with only a camera for initial victim identification and operator-generated mapping. Once a victim was potentially located, the second, slower robot was dispatched to the location with more specific victim identification sensors. The technical award winner was the team from the International University at Bremen (IUB) in Germany. It also deployed two robots but was recognized for its arena-mapping implementation, which used a proximity range finder to automatically generate obstacle maps of the environment. This team was the only one to demonstrate autonomous mapping during the competition, which is highly encouraged in the performance metric, but its use did not contribute quite enough points to earn the team a place award. Other interesting approaches included fully autonomous robots, a robot pulled almost directly from the middle-size soccer league, and even a blimp. The two fully autonomous teams demonstrated robots capable of navigating parts of the yellow arena but didn't produce maps showing victim identifications, another key performance criteria, so did not score well. Minor rule modifications proposed for 2004 might artificially limit the use of radio communications during missions to simulate radio signal dropout and interference that occurs at actual disaster sites. The intent is to encourage more development of autonomous behaviors and active tether management systems that are practical for eventual deployment.

For the second year, human factors researchers used the competition event to study human-robot interaction during missions. The operators, the interfaces to their robots, and the robots themselves were videotaped during missions. These video streams, along with objective monitoring of operator actions and interviews conducted immediately after each mission, captured the work load required to perform each task and provided the basis for the study of effectiveness and ease-of-use issues. A formal analysis of these data is under way with the goal of identifying effective interface components and methods so that other teams, and other applications, might benefit.[7]

RoboCup Junior

RoboCup Junior celebrated its fourth year of international competitions with a continued increase in levels of interest and participation, involving 74 teams (258 participants) from 16 countries worldwide.

The idea of RoboCup Junior was first introduced in 1998 as a version of robot soccer that uses an infrared-emitting ball to simplify vision and a pitch, with a grey-scale floor to simplify localization (Lund and Pagliarini 1999). In 2000, RoboCup Junior held its first international competition in Melbourne, Australia. A strong team of in-practice teachers, led by Brian Thomas, organized RoboCup Junior-2000 and developed three challenges, each geared toward students with different interests and abilities: (1) soccer, a two-on-two game based on the setup of Lund and Pagliarini (which was a one-on-one game) that adapts the rules of the RoboCup Small Size League; (2) sumo, a line-following challenge for intermediate-level students; and (3) dance, a creative challenge designed for primary-age students. The initiative has grown in popularity, with events colocated at every international RoboCup since Melbourne.

The first research into the effectiveness of RoboCup Junior as a hands-on learning environment was conducted in Melbourne. This research has continued since 2000, including a paper that won the Scientific Challenge Award at the 2002 RoboCup Symposium (Sklar, Eguchi, and Johnson 2003). This research has shown that many of the skills universally affected in a positive way as a result of RoboCup Junior preparation and participation fall within the realm of social and personal development, such as teamwork and self-confidence. Further study was conducted in 2003, and the results are forthcoming.

In Padua, teams could enter four different challenges: (1) one-on-one soccer, (2) two-on-two soccer, (3) dance, and (4) rescue (figure 11). Three different age groups were represented: (1) primary (to age 12), (2) secondary (ages 12–18, or end of high school), and (3) undergraduate. The biggest changes in the event from 2002 were the introduction of a newly designed rescue challenge and the development of a new entry-level soccer league for undergraduates, called the ULeague (figure 11). Note that some teams entered more than one challenge within their age group.

At RoboCup Junior-2003, soccer remained the most popular challenge, engaging 67 of the teams overall. Some of the secondary students took advantage of state-of-the-art technological improvements and used, for example, magnetic sensors for direction and ultrasonics for collision avoidance. LEGO MINDSTORMS continues to be the most popular medium for robot construction, but many teams, particularly in Asia, use the Elekit SOCCERROBO. More advanced teams, most notably from Australia and Germany, even constructed their hardware completely from scratch.

Robot dance continues to be very popular with students of all ages. As in the previous year, the standard was very high, demonstrating that dance has all the technical challenges of other junior events, combined with great opportunities for artistic creativity in music, choreography, and costume. This year, many participants chose to perform with their robots, including one team that sang and played music on guitar. Altogether, dance has grown to become one of the most popular spectator events at RoboCup.

The newly redesigned event of RoboCup Junior Rescue attracted participants in both primary and secondary teams. It is easy to get started with this event, but the challenge becomes more demanding as students raise their aspirations. We expect it to become much more popular in future years because of the progressive and personal nature of the challenge. The task for the robot is to follow a black line through a "building" (essentially a dollhouse) looking for "victims" (bodies cut from silver foil and green tape), which are laid across the black line. A number of rooms are connected by corridors and ramps across multiple stories, and robots have to deal with differing light levels in upper and lower levels. Points are awarded for the number of bodies detected as well as the fastest time to complete the course.

In the new ULeague challenge, teams from the United States, Canada, Australia, and Germany participated. The purpose of the ULeague is to provide an opportunity within RoboCup

Figure 11. RoboCup Junior-2003 Challenges.
Top: Dance. *Middle:* Rescue. *Bottom:* ULeague soccer.

Soccer Competitions

Simulation League
First Place: UVA TRILEARN, *University of Amsterdam,* Holland
Second Place: TSINGHUAELOUS, *Tsinghua University,* China
Third Place: BRAINSTORMERS, *University of Dortmund,* Germany

Small-Size Robot League
First Place: BIG RED, *Cornell University,* USA
Second Place: ROBOROOS, *The University of Queensland*, Australia
Third Place: FU FIGHTERS, *Freie Universitaet Berlin,* Germany

Middle-Size Robot League
First Place: FUSION, *Kyushu University and Fukuoka University,* Japan
Second Place: WINKIT, *Kanazawa Institute of Technology,* Japan
Third Place: PERSIA, *Isfahan University of Technology,* Iran

Four-Legged Robot League
First Place: RUNSWIFT, *University of New South Wales,* Australia
Second Place: UPENNALIZERS, *University of Pennsylvania,* USA
Third Place: NUBOTS, *The University of Newcastle,* Australia

Humanoid League — Louis Vuitton Cup
HITS DREAM, *Honda International Technical School,* Japan

Humanoid League — Walk
First Place: HITS DREAM, *Honda International Technical School,* Japan
Second Place: SENCHANS, *Osaka University Handai FRC,* Japan
Third Place: FOOT-PRINTS, *Private,* Japan

RoboCup Rescue

Rescue Simulation
First Place: ARIAN, *Sharif University of Technology,* Iran
Second Place: YOWAI, *The University of ElectroCommunications,* Japan
Third Place: S.O.S., Amir Kabir, *University of Technology,* Iran

Rescue Robot
First Place: ROBRNO, *Brno University of Technology,* Czech Republic
Second Place: CEDRA, *Sharif University of Technology,* Iran
Third Place: IUT MICROBOT, *Isfahan University of Technology,* Iran

Table 3. The Winning Teams.

for students to bridge the gap between RoboCup Junior and the senior leagues, such as the Small-Size League. In the ULeague setup, a common solution is provided for global vision and team communication, and the burden is on teams to devise coordinated behaviors for their robots and/or hardware platforms.

RoboCup Junior has seen strong growth in the number of female participants, particularly in the dance challenge, which provides a unique outlet for creativity. Although RoboCup Junior attracts an average of 15 female students overall (increased from 10 in 2000), the dance challenge at RoboCup Junior-2003 had 31 female participants. This trend has been duplicated in all the national open events held thus far, most notably in Australia where over half the RoboCup Junior dance participants were female. This level of participation is impressive because the scale of the Australian RoboCup Junior effort is such that each state has its own regional championship, and 500 students participate in the country's national RoboCup Junior event each year.

One of the most encouraging observations from this year's event was the level of cooperation between teams, especially between secondary and primary students. The students' preparation area was a hive of activity and intense pressure, but many of the older students took the time to help younger students with technical or programming problems. Many RoboCup Junior events will be occurring worldwide in 2004, including open events in Australia, Germany, Japan, Canada, and the United States—in addition to the annual international event at RoboCup-2004 in Lisbon.[8]

Conclusions

In this article, we brought attention to some of the important research achievements made at RoboCup-2003 in Padua, Italy. If we compare the performance of the teams and the scientific results illustrated at the symposium, with the fundamental problems introduced in some of the early seminal papers that appeared in the literature from 1997 to 1999, we can certify that remarkable advancements have already been achieved in the area of AI and autonomous robots. The RoboCup community is now a larger scientific environment that includes not only those who are simply interested in soccer robotics technology. New leagues, such as rescue robotics and humanoids, are quickly evolving and have already proved to be an excellent experimental test bed. The record peak of 1,244 registered participants, and 243 competing teams, has definitively made the annual RoboCup international competitions and conferences one of the most important meetings in the world, such as the International Joint Conference on Artificial Intelligence in the field of AI and the International Conference on Robotics and Automation and the International Conference on Intelligent Robots and Systems in the field of robotics (Adorni and Van der Hoek 2001).

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Notes

1. Log files of the games and further information can be found at the simulation league web site www.uni-koblenz.de/fruit/orga/rc03.

2. For more information on the Small-Size League, please visit the web site www-2.cs.cmu.edu/ brettb/robocup/.

3. More information on the Four-Legged League can be found at www.openr.org/robocup/.

4. For additional information on the Middle-Size League, please visit www.ais.fraunhofer.de/robocup/msl2003/.

5. Please see the homepage of the Humanoid League (www.ais.fraunhoferde/robocup/HL2004) and the mailing list for upcoming changes and developments.

6. Interested readers can find more information on the Rescue Simulation League at robomec.cs.kobe-u.ac.jp/robocup-rescue/.

7. More information can be found at www.isd.mel.nist.gov/RoboCup2003/.

8. For further information about events and rules for each challenge, refer to our web site: www.robocupjunior.org.

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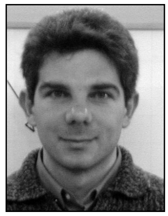

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A future issue of *AI Magazine* may contain additional, more in-depth (and technical) coverage of RoboCup. *– Ed.*