Overview of RoboCup-98

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Abstract

The Robot World Cup Soccer Games and Conferences (RoboCup) are a series of competitions and events designed to promote the full integration of AI and robotics research. Following the first RoboCup, held in Nagoya in 1997, RoboCup-98 was held in Paris from July 2–9, 1998, overlapping with the real World Cup soccer competition. RoboCup-98 included competitions in three leagues: the simulation league, the small-size real robot league, and the middle-size real robot league. Champion teams were CMUnited-98 (Carnegie-Mellon University) in both the simulation and the small-size real robot leagues, and CS-Freiburg (Freiburg, Germany) in the middle-size real robot league. RoboCup-98 also included a Scientific Challenge Award, which was given to three research groups (Electrotechnical Laboratory (ETL), Sony Computer Science Laboratories, Inc., and the German Research Center for Artificial Intelligence GmbH (DFKI)) for their simultaneous development of fully automatic commentator systems for RoboCup simulator league. Over 15,000 spectators watched the games and 120 international media provided worldwide coverage of the competition.

1 Introduction

The Robot World Cup Soccer Games and Conferences (RoboCup) are a series of competitions and events designed to promote the full integration of AI and robotics research. Following the first RoboCup, held in Nagoya in 1997 [Noda *et al.*1998],RoboCup-98, the Second Robot World Cup Soccer Games and Conferences, was held on July 2-9, 1998 at La Cité des Sciences et de L'Industrie in Paris, overlapping with the real 1998 World Cup finals in Paris [Asada1998]. It was organized by the University of Paris-VI and CNRS, and was sponsored by Sony Corporation, NAMCO Limited, and SUNX Limited, with official balls for the middle-size real robot league supplied by Molten Corporation. Over 15,000 people watched the games and over 120 international media (such as CNN, ABC, NHK, and TV-Aich) and prominent scientific magazines covered the competition.

RoboCup-98 had three kinds of leagues: the simulation league, the small-size robot league, and the middle-size robot league. Figure 1 shows the small-size robot league competition site and Figure 2 shows the middle-size robot league competition site. Although it was not an official RoboCup competition, the Sony Legged Robot Competition and Demonstration also attracted many spectators, especially children, who were attracted by the robot's appealing appearance and ability to move in a natural way. Three teams from Osaka University, CMU, and University of Paris-VI presented exhibitions of this robot, which is shown in Figure 3. In 1999, the Sony Legged Robot league will be added to the official RoboCup competitions [Veloso *et al.*1998]. Another popular adjunct to the competition was a soccer stadium, built by The University of Aahus using Lego Mind Storm, with figures of supporters that waved and cheered for the robot players.

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Figure 1: Small-size robot league competition site.

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Figure 2: Middle-size robot league competition site.

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Figure 3: Sony legged robot league competition site.

In addition to the robot championship awards, RoboCup awards a Scientific Challenge Award. This award was created as an equally prestigious—or even more prestigious—award for innovative and significant scientific advances achieved in RoboCup-related research. This year, the Scientific Challenge Award was given to three research groups, Electrotechnical Laboratory (ETL), Sony Computer Science Laboratories, Inc., and German Research Center for Artificial Intelligence GmbH (DFKI), for their simultaneous development of fully automatic commentator systems for RoboCup simulator league.

In this article, we review the challenge issues of each league and analyze the results of RoboCup-98. We compare the architectural differences between the leagues, summarize which research issues have been solved and how, and discuss those which have been left unsolved and remain as future issues. Following articles in this issue discuss the champion teams for each league, the legged robot demonstration, and the RoboCup commentator systems. A complete list of match results and additional information are available at the RoboCup web site *http://www.robocup.org/*.

2 Leagues and Approaches

RoboCup-98 had three kinds of leagues:

1. **Simulation league:** Each team consists of eleven programs, each controlling one of eleven simulated team members. The simulation is run using the Soccer Server developed by Itsuki Noda (details are available on the RoboCup web site). Each player has motion energy and distributed relatime sensing capabilities (vision and auditory), both of which are noisy and resource bounded. Communication is available between players and strict rules of soccer are enforced (e.g. off-sides).

2. **Small-size robot league:** The field is the size and color of a ping-pong table and up to five robots per team play a match with an orange golf ball. The robot size is limited to approximately 15cm^3. Typically robots are built by the participating teams and move at speeds of up to 2m/s. Global vision is allowed, offering the challenge of real-time vision-based tracking of five fast moving robots in each team and the ball.

3. **Middle-size robot league:** The field is the size and color of a three-by-three arrangement of ping-pong tables, and up to five robots per team play

a match with a Futsal-4 ball. The size of the base of the robot is limited to approximately 50cm in diameter. Global vision and sensing are not allowed. Goals are colored and the field is surrounded by walls to allow for possible distributed localization through robot sensing.

Each league has its own architectural constraints, and therefore research issues are slightly different for each one. We have published proposal papers [Kitano *et al.*1998, Asada *et al.*1998] about research issues in RoboCup initiative. For the synthetic agents in the simulation league, the following issues are considered:

- Teamwork among agents, from low-level skills such as dribbling and passing the ball to a teammate, to higher level skills involving execution of team strategies.
- Agent modeling, from primitive skills like recognizing agents' intents to pass the ball, to complex plan recognition of high-level team strategies.
- Multiagent learning, for on-line and off-line learning of simple soccer skills for passing and intercepting, as well as more complex strategy learning.

For the robotic agents in the robot leagues, both small and middle-size, the following issues are considered:

- Efficient real-time global or distributed perception possibly from different sensing sources.
- Individual mechanical skills of the physical robots, in particular target aim and ball control.
- Strategic navigation and action to allow for robotic teamwork, by passing, receiving and intercepting the ball, and shooting at the goal.

We held the first RoboCup competitions in August 1997, in Nagoya, in conjunction with IJCAI-97 [Kitano1998]. There were 28, 4, and 5 teams participating in the simulation, small-size robot, and middle-size robot leagues, respectively. The second RoboCup workshop and competitions took place in July 1998, in Paris [Asada1998] in conjunction with ICMAS-98 and AgentsWorld. The number of teams increased significantly from RoboCup-97 to 34, 11, and 16 participating teams in the simulation, small-size robot, and middle-size robot leagues respectively. Teams represented more than twenty countries. Every team had its own features, which were demonstrated during their matches with different degrees of success.

3 RoboCup Architectural Approaches

There are two kinds of structural issues in designing a robot team for RoboCup:

1. Physical structure of robots: actuators for mobility, kicking devices, perceptual facilities (cameras, sonar, bumper sensor, laser range finder) and computational facilities (CPUs, microprocessors).
2. Architectural structure of control software.

In the simulation league, the methods used to address both of these sets of issues are fixed, and therefore strategic team structure has been a primary research focus. On the other hand, in the robot leagues, individual teams have devised, built, and arranged their own robots. Although the small-size and middle-size robot leagues have their own architectural constraints, there are variations in the resource assignment and control structure of their robots. Table 1 shows how variations in architectural structure in terms of number of CPUs, cameras and communication bandwidth, and their arrangement, can be classified into six types, and the major issues they involve.

Table 1: Variations in architectural structure.

Type	CPU	Vision	Communication	Issues	Leagues
A	1	1 global	high	strategy	small-size
B	n	1 global	high	information sharing	small-size
C	1	1 global $+n$ local	high	sensor fusion; coordination	small-size
D	$1+n$	n local	high	multiple robots	middle-size
E	n	n local	high	sensor fusion; teamwork	middle-size
F	n	n local	low	teamwork; emergent cooperative behavior	middle-size & simulation

Communication between agents is allowed in all of the leagues, albeit bandwidth limitations apply in the simulation league and some middle size robot teams use no or at most low bandwidth equipment. Except for the middle-size robot league team Uttori United [K.Yokota *et al.*1998], the simulation league is so far the only league in which communication has been widely and successfully used to achieve coordinated team play. Most teams in the middle-size robot league use higher bandwidth radio-LANs for sensor fusion and information sharing.

4 Simulation League

The simulation league continues to be the most popular part of the RoboCup leagues, with 34 teams participating in RoboCup-98. As with RoboCup-97, teams were divided into leagues. In the preliminary round, teams played within leagues in a round-robin fashion, followed by a double-elimination round to determine the first three teams. Figure 4 summarizes the final simulation league results.

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Figure 4: Final tournament of the simulation league.

Teams in the RoboCup simulation league are faced with three strategic research challenges: multiagent learning, teamwork and agent modeling. All three are fundamental issues in multiagent interactions. The learning challenge involves on-line and off-line learning both by individuals and by teams (i.e., collaborative learning). One example of off-line individual learning is learning to intercept the ball, while an example of on-line collaborative learning is to adaptively change player positions and formations based on experience in a game.

The RoboCup Teamwork Challenge addresses issues of real-time planning, re-planning, and execution of multiagent teamwork in a dynamic adversarial environment. A team should generate a strategic plan, and execute it in a coordinated fashion, monitoring for contingencies and select appropriate remedial actions. The teamwork challenge interacts also with the third challenge in the RoboCup simulation league, that of agent modeling. In general, agent modeling refers to modeling and reasoning about other agent's goals, plans, knowledge, capabilities, or emotions. The RoboCup opponent modeling challenge calls for research on modeling a team of opponents in a dynamic, multiagent domain. Such modeling can be done on-line to recognize a specific opponent's actions, as well as off-line for a review by an expert agent.

At least some researchers have taken these research challenges to heart, so that teams at RoboCup97 and RoboCup98 have addressed at least some of the above challenges. In particular, out of the three challenges outlined, researchers have attacked the challenge of on-line and off-line learning (at least by individual agents). Thus, in some teams, skills such as intercept, and passing are learned off-line. The two final teams, namely CMUnited simulation (USA) as winner of the first place and AT-Humboldt-98 (Germany) as runner-up, included an impressive combination of individual agent skills and strategic teamwork.

Research in teamwork has provided advances in domain-independent teamwork skills (i.e., skills that can be transferred to domains beyond RoboCup)[Tambe *et al.*19 about roles and role reorganization in teamwork. However, opponent modeling, in terms of tracking opponents' mental state, has not received significant attention by researchers. There are however some novel commentator agents that have used statistical and geometric techniques to understand the spatial pattern of play.

5 Small-Size Robot League

The RoboCup-98 small-size robot league provides a framework to investigate the full integration of action, perception, and high-level reasoning in a team of multiple agents. Therefore, three main aspects need to be addressed in the development of a small-size RoboCup team: (i) hardware of physical robots; (ii) efficient perception; and (iii) individual and team strategy.

Although all of the eleven RoboCup-98 teams included distinguishing features at some of these three levels, it was shown to be crucial to have a *complete* team with robust hardware, perception, and strategy, in order to perform overall well. This was certainly the case for the four top teams in the competition, namely CMUnited-98 (USA), Roboroos (Australia), 5DPO (Portugal), and Cambridge (UK), who captured first, second, third, and fourth places respectively.

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Figure 5: Small-size robot final match.

Figure 5 shows a scene from the final match between CMUnited-98 and Queensland Roboroos (Australia), and Figure 6 presents the results of the final file=c:/usr/asada/figure/small98.EPS,width=90mm

Figure 6: Final tournament of the small-size robot league.

tournament in the small-size robot league. We now summarize the characteristics of the RoboCup-98 small-size teams and the research issues addressed.

Hardware: All of the eleven small-sized teams consisted of robots built by each participating group. The actual construction of robots within the strict size limitations offered a real challenge, but gave rise to many interesting physical and mechanical devices. Remarkably, the robots exhibited sensor-activated kicking devices (iXs and J-Star, Japan, Paris-6, France, and CMUnited-98, USA), sophisticated ball holding and shooting tools for the goalie robot (Cambridge, UK), and impressive compact and robust designs (Roboroos, Australia, and UVB, Belgium). All of the robots were autonomously controlled through radio communication by offboard computers.

Perception: Ten out of the eleven teams used a single camera overlooking the complete field. The ISpace (Japan) team included one robot with an onboard vision camera.

Global perception simplifies the sharing of information among multiple agents. However, at the same time it presents a research challenge for reliable and real-time detection of the multiple mobile objects – the ball, and five robots on each team. In fact, both detection of robot position and orientation and robot tracking need to be very effective. The frame rate of the vision processing algorithms clearly impacted the performance of the team. Frame rates reached 30 frames/sec as in the CMUnited-98 team.

In addition to the team color (blue or yellow), most of the teams used a second color to mark their own robots and provide orientation information, hence only about their own robots. Robot identification was achieved in general by greedy data association between frames. The 5DPO (Portugal) and the Paris-6 (France) teams had a robust vision processing algorithm that used patterns to discriminate among the robots and to find their orientation.

The environment in the small-size league is highly dynamic with robots and the ball moving at speeds between 1m/s and 2m/s. An interesting research issue consists of the prediction of the motion of the mobile objects to combine it with strategy. It was not clear which teams actually developed prediction algorithms. In the particular case of the CMUnited-98 team, prediction of the movement of the ball was successfully achieved and highly used for motion (e.g., ball interception) and strategic decisions (e.g., goaltender behavior and pass/shoot decisions).

Motion: In this RoboCup league, a foul is called when robots push each other. This rule offers another interesting research problem, namely obstacle avoidance and path planning in a highly dynamic environment. The majority of the teams in RoboCup-98 successfully developed algorithms for such difficult obstacle avoidance and the semifinal and final games showed smooth games that demonstrated impressive obstacle avoidance algorithms.

Strategy: Following up on several of the research solutions devised for RoboCup-97 both in simulation and in the small-size robots, at RoboCup-98, all of the small-size teams showed a role-based team structure. As expected, the goaltender played a very important role in each team. Similarly to the goaltender of CMUnited-97, the goaltender of most of the teams stayed parallel to the goal line and tried to stay aligned with or intercept the ball. The goaltender represented a very important and crucial role. Especially notable were the goaltenders of Roboroos, CMUnited-98, and Cambridge.

Apart for CMUnited-98 which had a single defender and three attackers, most of the other teams invested more heavily in defense, assigning two robots as defenders. In particular, defenders in the UVB, Belgium and Paris-8 teams occupied key positions in front of the goal making it difficult for other teams to path plan around them and to try to devise shots through the reduced open goal areas. Defending with polygonally-shaped robots proved to be hard, as fine control of the ball is difficult. In fact, a few goals for different teams were scored into their own goals due to small movements of the defenders or goaltender very close to the goal. It is clearly still an open research question how to control the ball more accurately.

Finally, it is interesting to note that one of the main features of the winning CMUnited-98 team is its ability to collaborate as a team. Attacking robots continuously evaluate (30 times per second) their possible actions, namely either to pass the ball to another attacking teammate or to shoot directly at the goal. A decision-theoretic algorithm is used to assign the heuristic and probabilistic based values to the different possible actions. The action with the maximum value is selected. Furthermore, in the CMUnited-98 team, a robot who was not the one actively pursuing the ball is not merely passive. Instead, each attacking robot *anticipates* the needs of the team and positions itself in the location that maximizes the probability of a successful pass. CMUnited-98 uses a multiple-objective optimization algorithm with constraints to determine this strategic positioning. The objective functions minimize repulsion from other robots and maximize attraction to the ball and to the attacking goal.

6 Middle-Size Robot League

The middle-size robot league this year had 16 teams. They were divided into four groups, each of which consisted of four teams taking into account regional distribution, and preliminary games took place in each group. Then, the best two teams from each group advanced to the playoff tournament, which is summarized in Figure 7. Figure 8 shows a picture of the quarter final match between Osaka Trackies and NAIST.

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Figure 7: Playoff tournament of the middle-size robot league.

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Figure 8: A match from the middle-size robot league.

Excitement both among participants and spectators intensified in the semifinals, both of which were matches of Japanese against German teams. In the first semifinal, University of Freiburg won 3:0 against Osaka University. The second semifinal between Uttori United and University of Tübingen ended with a draw after regular time. Penalty shootouts did not produce a decision either, so a "technical challenge" was used to decide. In the technical challenge, a target goal is selected and the ball is placed in the middle of the field. A single robot is positioned on the field between the goal and the ball, heading towards the goal. The task is to find the ball, move it towards the goal, and finally shoot it into the goal. The time the robots take to complete the task determines the winner. Tübingen won the technical challenge and proceeded to the finals. The final itself was convincingly won 3:0 by the University of Freiburg. This game also produced the nicest goal shot in the whole tournament, when the Freiburg robot took the ball from its "left hand" onto its "right hand" and scored.

A very encouraging result from Paris is that all except two scheduled games could actually be played. Considering the large number of new teams, which were built within the nine months since Nagoya, this is a considerable achievement for most groups. Teams can now use their technological base to investigate open problems, engineer new solutions, and conduct interesting experiments (see [Shen *et al.*1998, Price1998, Suzuki *et al.*1998, Nakamura *et al.*1998]).

Technological Progress: All participants agreed that the overall level of play improved dramatically since Nagoya. What are the major technological innovations that contributed to this improvement?

1. Many of the new teams used off-the-shelf platforms as mobile bases, such as Activmedia's Pioneer-1 and Pioneer-AT robots (used by six teams) or Nomadics' Scout robot (used by one team). These platforms are not perfect, therefore many teams substantially modified the robot and added additional equipment like vision systems, kicking devices, communication devices, and embedded PCs for onboard computation.

2. The vision systems seem to have improved a lot since Nagoya. Many teams could detect and track the ball and the two colored goals much more reliably than one could observe in Nagoya. However, there are still many problems with the perceptual capabilities of the robots, especially detecting teammates and opponents, and the improvement of the robots' visual capabilities will remain a central research topic in RoboCup.

3. A number of teams featured kicking mechanisms on their robots. A simple, yet powerful approach were pneumatic kickers. Other robots used a solenoid-based activation device. The kicking devices produced much higher ball

accelerations than the robots could achieve by simply pushing the ball. One robot even scored a goal directly after kickoff. Overall, with kicking devices robots could move the ball significantly better, which is one of the research issues in the middle-size robot league.

4. Several teams attached passive devices such as shaped metal sheets or springs (nicknamed “fingers” or “hands”) to their robots, thereby creating a concave surface for improved ball handling (moving, receiving, passing). With hands, robots could better move and turn with the ball, and often could retrieve the ball once it was stuck against the walls and bring the ball back into play.

Many teams used an architectural team structure according to schemes D or E in Table 1 and used some kind of radio communications to coordinate and control their robots. However, frequency conflicts, noise produced by mobile phones and equipment used by film teams and the press often caused serious problems to communication. More reliable and flexible communication devices are needed in future. An alternative approach is to reduce dependence on such communications equipment and use a team structure according to scheme F in Table 1.

Research Results: One observation from the games in Paris is that creating a good goalie can dramatically improve overall team performance, and is somewhat simpler to build than a good field player. Several teams used omnidirectional vision systems that allowed their robots both to track their position in front of the goal as well as ball position [Suzuki *et al.*1998, Price1998] since Osaka used it in the first RoboCup in Nagoya. USC’s Ullanta used a fast IS Robotics/RWI B14 base as goalie, together with a rotating “hand” and a Cognachrome vision system; it did not allow a single goal. The most successful goalie was the one by University of Tübingen, which did not allow a single goal, not even in penalty shootouts, until the final game and probably was the main reason why Tübingen made it to the finals.

Two Japanese teams, Uttori United [K.Yokota *et al.*1998] and Osaka University, demonstrated excellent ball handling capabilities. The Uttori robots feature a sophisticated omnidirectional drive system that allowed their robots to closely circle around the ball once they found it without visually loosing track of the ball (which happened often to other teams) until the robot’s kicking paddle is heading towards the ball and the goal. Then the robot starts to move slowly towards the goal. The kicking device is designed such that the robot can push the ball across the floor without the ball starting to roll, thereby reducing the risk to loose the ball. Near the goal, the kicking paddle gives the ball a sufficiently strong kick to roll it away about half a meter. The robot then turns in order to head two fans towards the ball, activates the fans and blows the ball into the goal.

The new robots by Osaka University also exhibited very strong ball handling. Once it found the ball it could move rapidly across the field, guiding the ball close to its base, all the way into the opponents' goal. A main advantage over Uttori's approach is the higher speed they could achieve.

The winning strategy applied by Freiburg [Gutmann and Nebel1998] addressed a combination of issues. The distinguishing feature of their robots was the use of a laser range finder, which provides fast and accurate range data, on each of their five Pioneer-1 robots. Freiburg applied their extensive work in laser-based self-localization to outperform teams using just vision systems. By matching the laser scan data against the known walls surrounding the field, they could not only determine their own position and orientation on the field, but also the position of the other robots. Via radio-LAN the robots exchanged messages with a central server, which integrated all individual world models. By asking each of their robots about its own position, they could distinguish between teammates and opponents. The server in turn sent out a global, integrated world model to the robots, which was used to determine actions and to plan paths. The world model was precise enough to allow robots to choose and aim at the corner of the goal into which they would kick, or to give a pass to a teammate. The individual players were sufficiently autonomous to perform reasonable actions even when communication breaks down. However, team play would severely suffer or be impossible in this case. As a result, their approach seems to based largely on global positioning and centralized control (Type D in Table 1), even though each player has its own CPU to detect a ball and to control its body. This contrasts with type E in Table 1, which is a more typical architecture in the middle-size league.

7 Future Issues

Simulation League

Major progress from RoboCup-97 to RoboCup-98 has been shown in more dynamic and systematic teamwork. In particular, introduction of the offside rule and improvement of individual play forces flexible team play. However, even in RoboCup-98 this is still at a preliminary level. For example, tactics to escape from offside traps were still passive even in champion teams. In future RoboCups, such tactics will require recognition of intention of opponent players/teams. In this stage, opponent modeling and management of team strategies would become more important. Similarly, on-line learning will become more important, because team strategies should be changed during a match according to strategies of opponent teams.

While the research displayed in the RoboCup simulation league is encouraging, it is fair to say that it has been difficult for researchers to extract general lessons learned and to communicate such lessons to a wider audience in multi-agents or AI. To facilitate such generalization, a new domain, *RoboCup Rescue* is being designed. In RoboCup Rescue, the focus will be on rescuing people stranded in a disaster area (where the disaster may be earthquake, fire, floods, or some combination of these events). This domain will not only emphasize the research issues of teamwork, agent modeling and learning, but in addition, raise novel issues in conflict resolution and negotiation. This domain will enable researchers to test the generality of their ideas and test their effectiveness in two separate domains.

Small-Size Robot League

The small-size robot league provides a very rich framework for the development of multiagent robotic systems. We look forward to advancing understanding of several issues, including the limitations imposed by the size restrictions on onboard capabilities; the robustness of global perception and radio communication; and strategic teamwork. One of the interesting open questions is the development of algorithms for on-line learning of the strategy of the opponent team and for the real-time adaptation of one's strategy in response. Finally, similarly to the simulation and middle-size robot leagues, we want to abstract from our experience algorithms that will be applicable beyond the robotic soccer domain.

Middle-Size Robot League

Despite the encouraging development of the middle-size robot league, we have to carefully review our current testbed and slowly adapt it to foster research in new directions and new areas. In most cases, this will require a slow evolution of rules.

The current focus on colors to visibly distinguish objects exerts a strong bias for research in *color-based* vision methods. It is desirable to permit other approaches as well, such as using *edges*, *texture*, *shape*, *optical flow* etc., thereby widening the range of applicable vision research within RoboCup.

Another issue is the development of better obstacle avoidance approaches. Currently, most robots except NAIST [Nakamura *et al.*1998] and a few others cannot reliably detect collisions with walls or other robots. Solving the charging problem using a rich set of onboard sensors is another major field of future research for RoboCup teams.

Finally, the use of communication in the different leagues is another active research topic. Communication allows interesting research [K.Yokota *et al.*1998] in a variety of topics, including multirobot sensor fusion and control. We want to explore limited communication environments and its relationship to agent autonomy, and learning of cooperative behavior.

8 Conclusion

As a grand challenge, RoboCup is definitely stimulating a wide variety of approaches, and has produced rapid advances in key technologies. With a growing number of participants RoboCup is set to continue this rapid expansion. With its three leagues, RoboCup researchers face an unique opportunity to learn and share solutions in three different agent architectural platforms.

RoboCup-99, the third Robot World Cup Soccer Games and Conferences, will be held in Stockholm in August 1999, in conjunction with the Sixteenth International Joint Conference on Artificial Intelligence (IJCAI-99). In addition to continuing the existing leagues, RoboCup-99 introduces the Sony legged robot league as an official RoboCup competition, as well as fielding more teams than the 1998 exhibition games and demonstrations.

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