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Overview of RoboCup-98

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■ 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, Japan, in 1997, RoboCup-98 was held in Paris from 2–9 July, overlapping with the real World Cup soccer competition. RoboCup-98 included competitions in three leagues: (1) the simulation league, (2) the real robot small-size league, and (3) the real robot middle-size league. Champion teams were CMUNITED-98 in both the simulation and the real robot small-size leagues and CS-FREIBURG (Freiburg, Germany) in the real robot middle-size league. RoboCup-98 also included a Scientific Challenge Award, which was given to three research groups for their simultaneous development of fully automatic commentator systems for the RoboCup simulator league. Over 15,000 spectators watched the games, and 120 international media provided worldwide coverage of the competition.

RoboCup-98, the Second Robot World Cup Soccer Games and Conferences, was held on 2–9 July at La Cité des Sciences et de L'Industrie in Paris, overlapping with the real 1998 World Cup finals in Paris (Asada 1998). It was organized by University of Paris-VI and the Centre National de la Recherche Scientifique and was sponsored by Sony Corporation, NAMCO Limited, and SUNX Limited, with official balls for the middle-size 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 leagues: (1) simulation, (2) real robot small size, and (3) real robot middle size. Figure 1 shows the small-size–league competition site, and figure 2 shows the middle-size–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, Carnegie Mellon 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 Aarhus using Lego Mindstorms, with figures of supporters that waved and cheered for the robot players.

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—(1) Electrotechnical Laboratory (ETL); (2) Sony Computer Science Laboratories, Inc.; and (3) German Research Center for Artificial Intelligence GmbH (DFKI)—for their simultaneous development of fully automatic commentator systems for the 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 issues that have been left unsolved and remain as future issues. Other 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, www.robocup.org/.

Figure 1. Real Robot Small-Size–League Competition Site.

Figure 2. Real Robot Middle-Size–League Competition Site.

Leagues and Approaches

RoboCup-98 had three leagues: (1) simulation, (2) small size real robot, and (3) middle size real robot.

Simulation league: Each team consists of 11 programs, each controlling 1 of 11 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 sensing capabilities (vision and auditory), both of which are resource bounded. Communication is available between players, and strict rules of soccer are enforced (for example, offsides). This league is mainly for researchers who might not have the resources for building real robots but are interested in complex multiagent reasoning and learning issues.

S**mall-size real robot league:** The field is the size and color of a Ping Pong table, and as many as five robots a team play a match with an orange golf ball. The robot size is limited to approximately 15 centimeters[3]. Typically, robots are built by the participating teams and move at speeds as high as 2 meters/second. Global vision is allowed, offering the challenge of real-time vision-based tracking of five fast-moving robots in each team and the ball.

Middle-size real robot league: The field is the size and color of a 3 × 3 arrangement of Ping Pong tables, and as many as 5 robots a team play a match with a Futsal-4 ball. The size of the base of the robot is limited to approximately 50 centimeters in diameter. Global vision is 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; therefore, research issues are different for each one. We have published proposal papers (Asada et al. 1998; Kitano et al. 1998) about research issues concerning the RoboCup initiative. For the synthetic agents in the simulation league, the following issues are considered:

First is teamwork among agents, from low-level skills such as passing the ball to a teammate to higher-level skills involving execution of team strategies.

Second is agent modeling, from primitive skills such as the recognition of agents' intents to pass the ball to complex plan recognition of high-level team strategies.

Third is multiagent learning for online and offline learning of simple soccer skills for passing and intercepting as well as more complex strategy learning.

For the robotic agents in the real robot

leagues, both small and middle size, the following issues are considered:

First is efficient real-time global or distributed perception, possibly from different sensing sources.

Second is individual mechanical skills of the physical robots, in particular, target aim and ball control.

Third is strategic navigation and action to allow for robotic teamwork, by passing, receiving, and intercepting the ball and shooting at the goal.

More strategic issues are dealt with in the simulation league and the small-size real robot league, but acquiring more primitive player behaviors is the main concern of the middle-size real robot league.

We held the first RoboCup competitions in August 1997 in Nagoya, Japan, in conjunction with the Fifteenth International Joint Conference on Artificial Intelligence (IJCAI-97) (Kitano 1998). 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 (Asada 1998) in conjunction with the 1998 International Conference on Multiagent Systems 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 20 countries. Every team had its own features, which were demonstrated during their matches with different degrees of success.

RoboCup Architectural Approaches

There are two structural issues to consider in designing a robot team for RoboCup: (1) the physical structure of the robots: actuators for mobility, kicking devices, perceptual facilities (cameras, sonar, bumper sensor, laser range finder), and computational facilities (central processing units [CPUs], microprocessors) and (2) the architectural structure of control software.

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

Figure 3. Sony Legged Robot–League Competition Site.

Communication between agents to coordinate individual playing behaviors (for example, when passing the ball) is allowed in all the leagues. However, this type of communication has only been used in the simulation league and by team UTTORI in the real robot middle-size league (Yokota et al. 1999).

Simulation League

The simulation league continues to be the most popular part of the RoboCup leagues, with 34 teams participating in RoboCup-98, which is a slight increase over the number of participants at RoboCup-97. 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.

Teams in the RoboCup simulation league are faced with three strategic research challenges:

Type	CPU	Vision	Issues	Legged League
A	1	1 global	Strategy	Small size
B	*n*	1 global	Sharing of information	Small size
C	1	1 global + *n* local	Sensor fusion, coordination	Small size
D	1 + *n*	*n* local	Multiple robots	Middle size
E	n	*n* local	Sensor fusion, teamwork	Middle size and simulation

Table 1. Variations in Architectural Structure.

(1) multiagent learning, (2) teamwork, and (3) agent modeling. All three are fundamental issues in multiagent interactions. The learning challenge involves online and offline learning both by individuals and by teams (that is, collaborative learning). One example of offline individual learning is learning to intercept the ball, and an example of online 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, replanning, 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 also interacts 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 online to recognize a specific opponent's actions as well as offline for a review by an expert agent.

At least some researchers have taken these research challenges to heart, so that teams at RoboCup-97 and RoboCup-98 have addressed at least some of these challenges. In particular, of the three challenges outlined, researchers have attacked the challenge of online and offline learning (at least by individual agents). Thus, in some teams, skills such as intercept and passing, are learned offline. The two final teams, namely, CMUNITED simulation (United States) as the first-place winner and ATHUMBOLDT-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 (that is, skills that can be transferred to domains beyond RoboCup) 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.

Small-Size Real Robot League

The RoboCup-98 small-size real robot league provides a framework for investigating 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: (1) hardware of physical robots, (2) efficient perception, and (3) individual and team strategy.

Although all 11 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 to perform well overall. This was certainly the case for the four top teams in the competition, namely, CMUNITED-98 (United States), ROBOROOS (Australia), 5DPO (Portugal), and CAMBRIDGE (United Kingdom), which captured first, second, third, and fourth places, respectively.

Figure 5 shows a scene from the final match between CMUNITED-98 and ROBOROOS, and figure 6 presents the results of the final tournament in the small-size robot league. We now summarize the characteristics of the RoboCup-98 small-size teams and the research issues addressed.

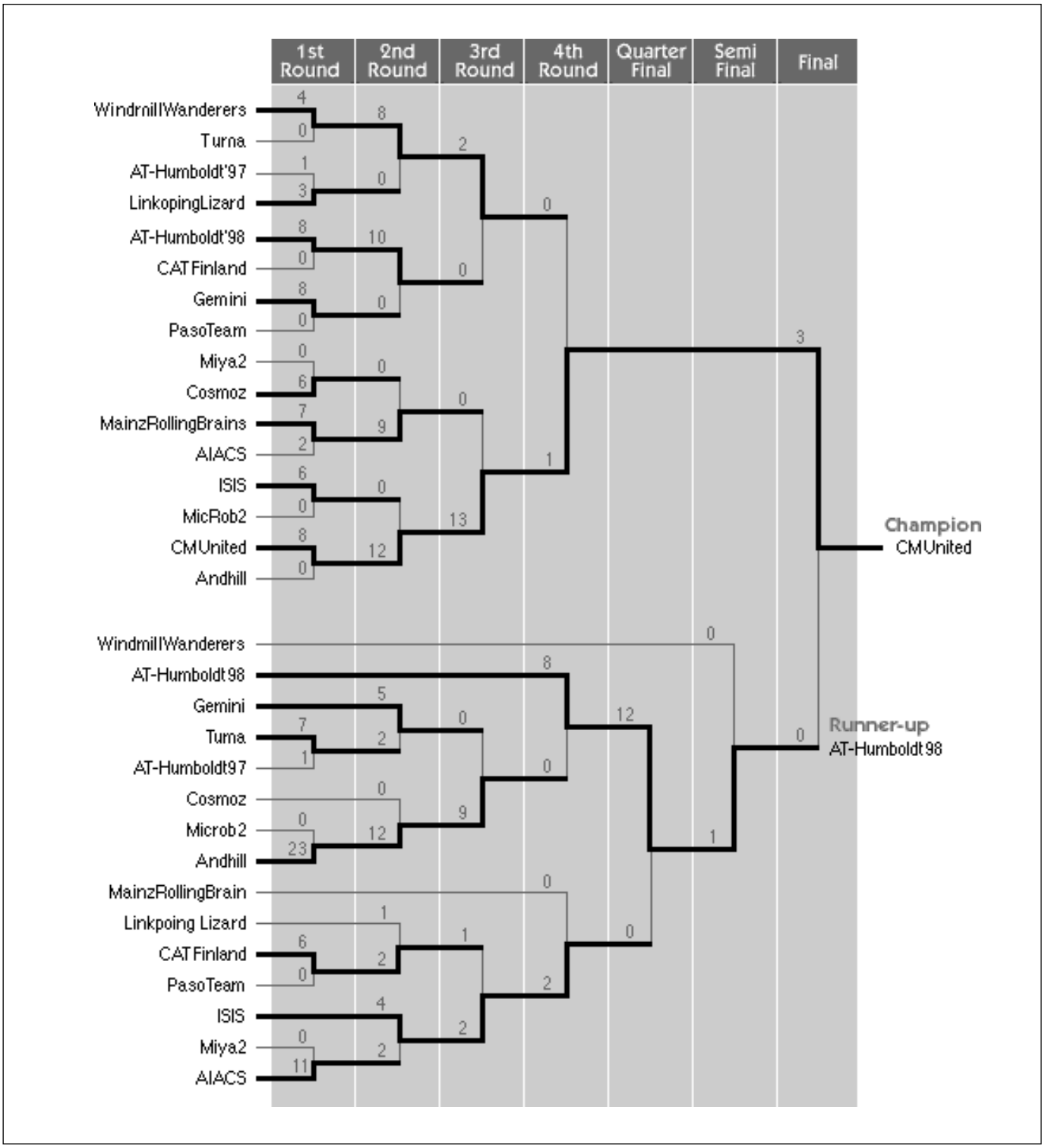

Figure 4. Final Tournament of the Simulation League.

Hardware

All 11 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 JSTAR, Japan; PARIS6, France; and CMUNITED-98, United States), sophisticated ball-holding and -shoot-

Figure 5. Real Robot Small-Size Final Match.

ing tools for the goalie robot (CAMBRIDGE, United Kingdom), and impressive compact and robust designs (ROBOROOS, Australia, and UVB, Belgium). All the robots were autonomously controlled through radio communication by off-board computers.

Perception

Ten of the 11 teams used a single camera overlooking the complete field. The ISPACE (Japan) team included one robot with an on-board 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 effective. The frame rate of the vision-processing algorithms clearly affected the performance of the team. Frame rates reached 30 frames a second, as with 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 only about their own robots. Robot identification was achieved, in general, by greedy data association between frames. The 5DPO (Portugal) and the PARIS6 (France) teams had a robust vision-processing algorithm that used patterns to discriminate among the robots and find their orientation.

The environment in the small-size league is highly dynamic, with robots and the ball moving at speeds between 1 meter a second and 2 meters a second. An interesting research issue is combining the prediction of the motion of the mobile objects with strategy. It was not clear which teams actually developed prediction algorithms. With the CMUNITED-98 team, prediction of the movement of the ball was successfully achieved and highly used for motion (for example, ball interception) and strategic decisions (for example, goal-tender 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

At RoboCup-98, all the small-size teams showed a role-based team structure, following up on several of the research solutions devised for RoboCup-97 in both the simulation and the small-size robot leagues. As expected, the goal tender played an important role on each team. Similar to the goal tender of CMUNITED-97, the goal tender of most of the teams stayed parallel to the goal line and tried to stay aligned with or intercept the ball. The goal tender represented an important and crucial role. Especially notable were the goal tenders of ROBOROOS, CMUNITED-98, and CAMBRIDGE.

Apart from 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 on the UVB, BELGIUM, and PARIS8 teams occupied key positions in front of the goal, making it difficult for other teams to path plan around them and try to devise shots through the reduced open goal areas. Defending with polygon-shaped robots proved to be hard because fine control of the ball is difficult. In fact, a few goals for different teams were scored into their own goals because of small movements by the defenders or goal tender close to the goal. How to control the ball more accurately is clearly still an open research question.

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 a second) their possible actions, namely, either to pass the ball to another attacking teammate or shoot directly at the goal. A deci-

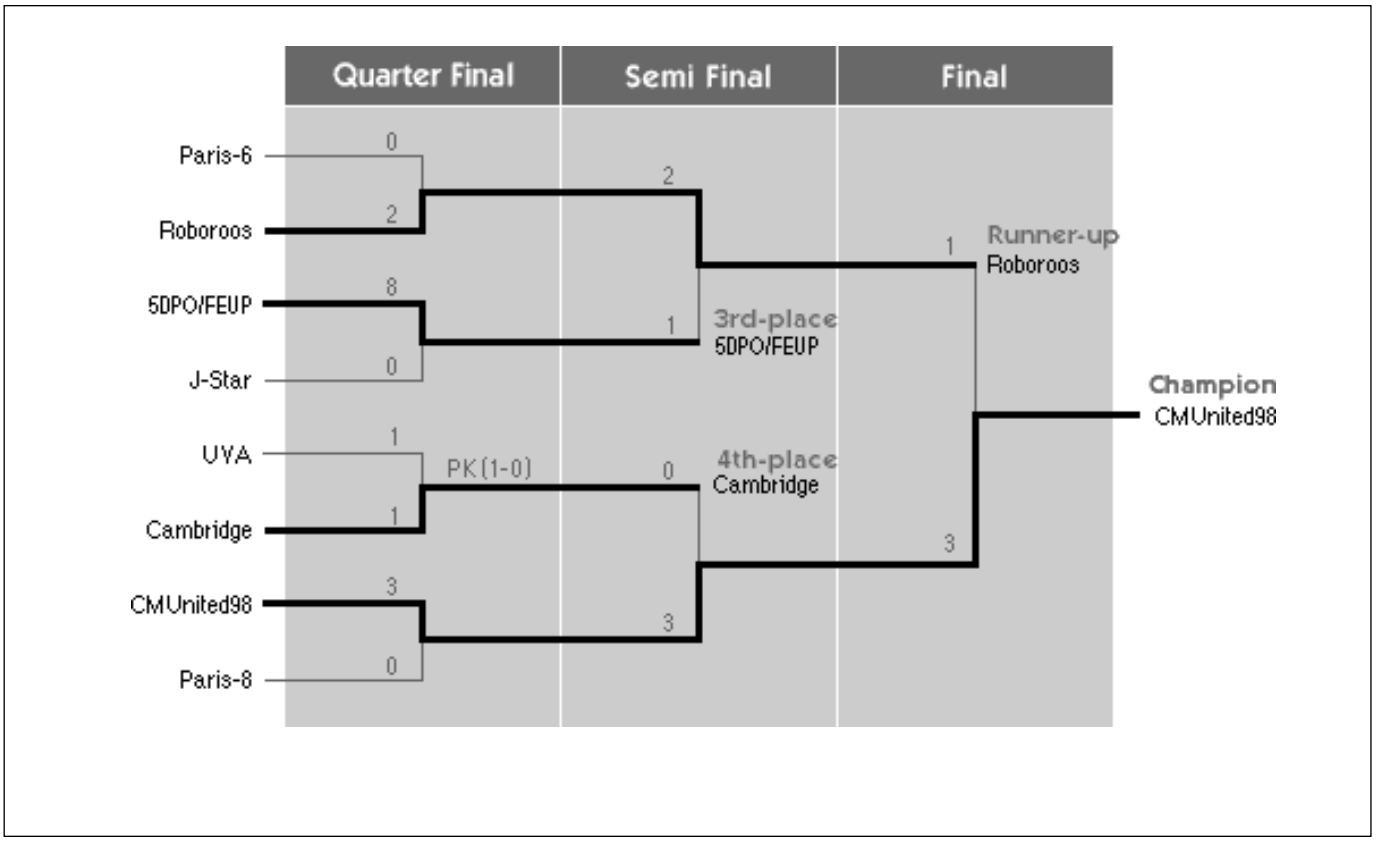

Figure 6. Final Tournament of the Small-Size League.

sion-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, with the CMUNITED-98 team, a robot that is 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 maximize repulsion from other robots and minimize attraction to the ball and the attacking goal.

Middle-Size Real Robot League

The middle-size league this year had 18 entries, but the DEAKIN BLACK KNIGHTS (Deakin University, Andrew Price, Australia) had fatal machine problems, and the Iranian team could not attend the official games because of their late arrival as a result of a visa problem (however, they played several exhibition games). The remaining 16 teams were divided into 4 groups, each of which consisted of 4 teams considering regional distribution. Preliminary games took place in each group. Then, the best two teams from each group advanced to the final tournament, which is summarized in figure 7. Figure 8 shows a quarter-final match between OSAKA TRACKIES and NAIST.

Excitement among participants and spectators intensified during the semifinals, both of which were matches between Japanese and German teams. In the first semifinal, the University of Freiburg won 3:0 against Osaka University. The second semifinal between UTTORI UNITED and the 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 the outcome of the match. 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 toward the goal. The task is to find the ball, move it toward 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 finals itself were convincingly won 3:0 by the University of Freiburg. This game also saw the nicest goal shot in the whole tournament, when the

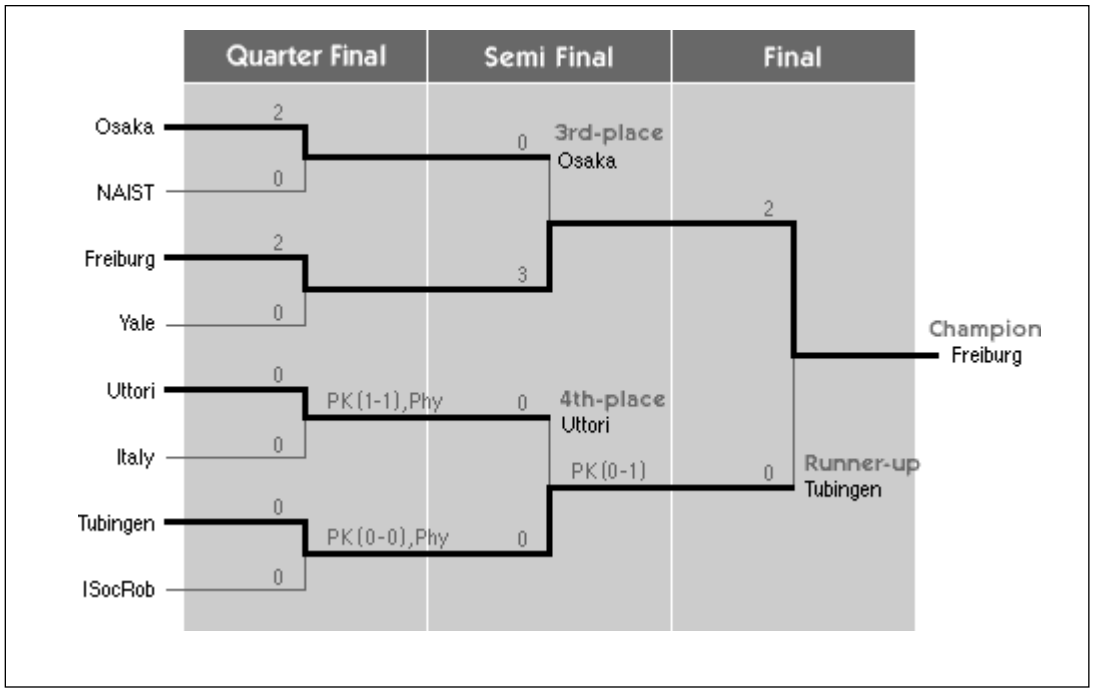

Figure 7. Final Tournament of the Middle-Size League.

Freiburg robot took the ball from its "left hand" and put it into its "right hand" and scored.

An encouraging result from Paris was that all but two scheduled games could actually be played. When considering the large number of new teams, which were built within the nine months since Nagoya, this achievement is considerable for most groups. Teams can use their technological base to investigate open problems, engineer new solutions, and conduct interesting experiments (Nakamura et al. 1999; Price and Jones 1999; Shen et al. 1999; Suzuki et al. 1999).

Technological Progress

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

First, many of the new teams used off-the-shelf platforms, such as Activmedia's PIONEER1 and PIONEERAT robots (used by six teams) or a Nomadics' SCOUT robot (used by one team). These platforms are not perfect; therefore, many teams substantially modified the robot and added equipment such as vision systems, kicking devices, communication devices, and embedded PCs for on-board computation.

Second, many teams now seem to have vision systems that work reasonably well, at least much better than what we saw in Nagoya. However, there are still many problems with the perceptual capabilities of the robots, especially when detecting other agents, and vision will remain a central research topic in RoboCup.

Third, a number of teams featured kicking mechanisms on their robots. A simple, yet powerful approach was the pneumatic kicker. 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.

Finally, 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, although the use of such hands is still under discussion.

Despite the architectural structures shown in table 1, many teams used some kind of radio communication to control their robots. However, frequency conflicts, noise produced by mobile phones, and equipment used by film teams and the press often caused serious problems with communication. Less dependence on such communication is expected in the future.

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 to track their position in front of the goal as well as the ball position (Price and Jones 1999; Suzuki et al. 1999); Osaka used it in the first RoboCup. USC's ULLANTA used a fast RWI (Real-World Interface) B14 base as goalie, together with a rotating "hand" and a Cognachrome vision system; it did not allow a single goal. Probably the most successful goalie was the one by the University of Tübingen, which did not allow a single goal, not even in penalty shootouts, until the final game; this was the main reason Tübingen made it to the finals. Two Japanese teams, UTTORI UNITED (Yokota et al. 1999) and Osaka University, demonstrated excellent ball-handling capabilities. The UTTORI robots featured a sophisticated omnidirectional drive system that allowed them to closely circle around the ball once they found it, without visually losing track of the ball (which happened often to other teams), until the robot's kicking paddle was heading toward the ball and the goal. Then, the robot started to move slowly toward 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 of losing the ball. Near the goal, the kicking paddle gave the ball a sufficiently strong kick to roll it away about half a meter. The robot then turned to head two fans toward the ball, activated the fans, and blew the ball into the goal.

The new robots by Osaka University also exhibited 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. The main advantage over UTTORI's approach is the higher speed that could be achieved.

The winning strategy applied by FREIBURG (Gutmann at al. 1999) addressed a combination of issues. The distinguishing feature of its robots was the use of a laser range finder, which provided fast and accurate range data on each of its five PIONEER1 robots. FREIBURG applied its 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. Using a radio local area network, the robots exchanged messages with a central server, which integrated all individual world models. By asking each of the 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 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. However, team play would severely suffer or be impossible in this case. As a result, their approach seemed to be 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 control its body. This architecture contrasts with type E in table 1, which is typical of the middle-size league.

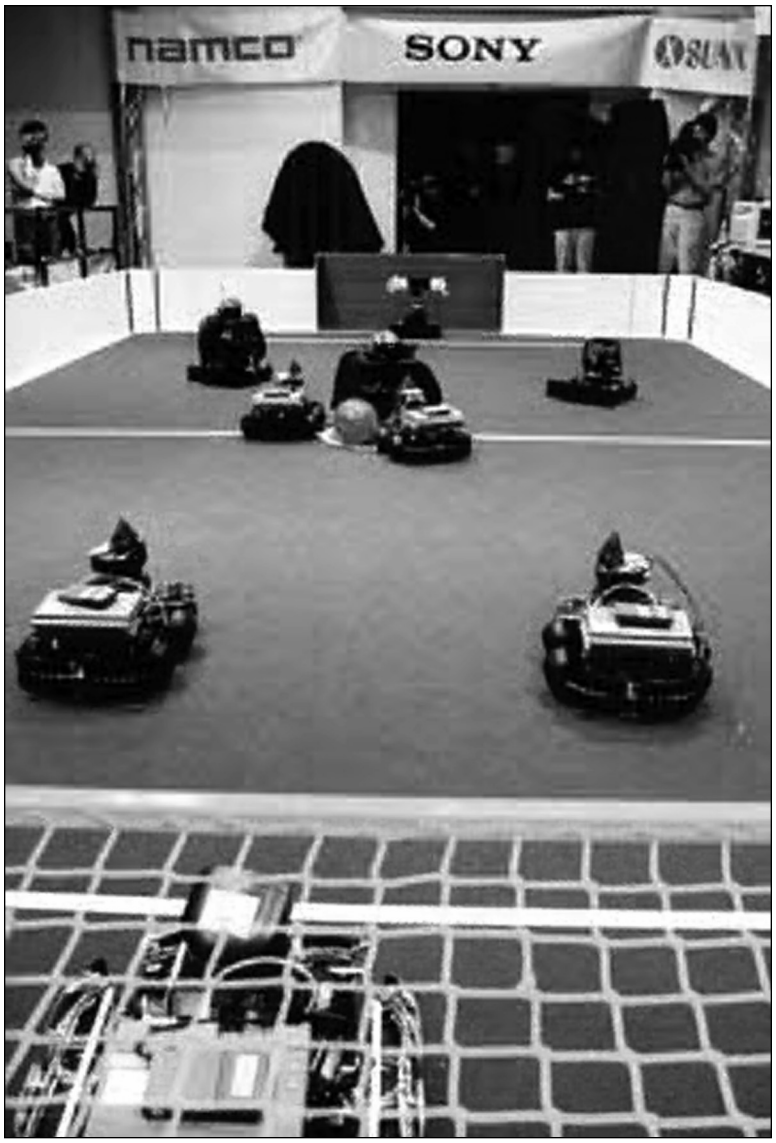

Figure 8. A Match from the Real Robot Middle-Size League.

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 offsides rule and improvement in individual play forces flexible team play. However, even in RoboCup-98, team play 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, online learning will become more important because team strategies should be changed during a match according to the strategies of opponent teams.

Although 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 communicate such lessons to a wider audience in multiagents 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 might 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, it will 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.

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

Real Robot Middle-Size League: Despite the encouraging development of the middle-size league, we have to carefully review our current test bed and slowly adapt it to foster research in new directions and areas. In most cases, this adaptation 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 the use of edges, texture, shape, optical flow, and so on, 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. 1999) and a few others, cannot reliably detect collisions with walls or other robots. Solving the charging problem using a rich set of on-board sensors is another area of future research for RoboCup teams.

Finally, the use of communication in the different leagues is another active research topic. Communication allows interesting research (Yokota et al. 1999) in a variety of topics, including multirobot sensor fusion and control. We want to explore limited communication environments and their relationship to agent autonomy as well as the learning of cooperative behavior.

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 a unique opportunity to learn and share solutions in three different agent architectural platforms.

RoboCup-99, the third Robot World Cup Soccer Games and Conferences, was 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 introduced the Sony legged robot league as an official RoboCup competition; it also fielded more teams than the 1998 exhibition games and demonstrations.

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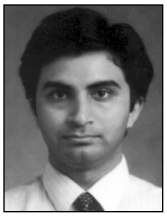

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