RoboCup 2001

A Report on Research Issues that Surfaced during the Competitions and Conference

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RoboCup-2001, the fifth international RoboCup competition and conference, was held for the first time in the United States, following RoboCup-2000 in Melbourne, RoboCup-1999 in Stockholm, RoboCup-1998 in Paris, and RoboCup-1997 in Osaka. RoboCup is a research-oriented initiative that pioneered the field of multirobot research starting in 1996 [1]. In those days, most robotics research was focused on single-robot issues. RoboCup opened a new horizon for multirobot research by focusing on teams of robots facing other teams of robots to accomplish specific goals. This challenging objective offers a broad and rich set of research and development questions; to wit, the construction of mechanically sound and robust robots, real-time effective perception algorithms, and dynamic behavior-based approaches to support teamwork.

Background

RoboCup has been a truly research-oriented endeavor. Every year, RoboCup researchers analyze the progress of the research and extend the competitions and demonstrations in the different leagues to create new challenges. The ultimate goal of RoboCup is to reach a point where teams of robots can successfully compete with human players. The RoboCup events move towards this goal.

This article discusses, in detail, each one of the events at RoboCup-2001 with a focus on leagues with real robots. As an overview of the complete RoboCup-2001, and as an introduction to this article, we provide a short description of the RoboCup-2001 events.

International Symposium

The international symposium consists of two days of technical paper presentations addressing artificial intelligence (AI) and robotics research of relevance to RoboCup. Twenty papers and 42 posters were successfully presented in perception and multiagent behaviors. The proceedings will be published by Springer and edited by program chairs Andreas Birk, Silvia Coradeschi, and Satoshi Takodoro.

Two Simulation Leagues

The *soccer simulator* competition includes teams of 11 fully distributed software agents. The framework consists of a server that simulates the game and changes the world according to the actions that the players want to execute. The server interacts with each of the players' programs on a server/client basis. This soccer server simulation environment has become more challenging and more realistic every year. The competition at Robo- Cup-2001 included heterogeneous players in the sense that players are modeled with different capabilities. In addition, it also included the first Coach Competition, where a "coach" agent can observe the complete game and interact periodically with individual players using a predefined language of commands.

The RoboCup *simulation rescue* competition, with teams of fully distributed software agents, provides a disaster scenario in

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which teams with different capabilities, e.g., firefighters, police crews, and medical teams, need to search for and rescue victims of the disaster. This event was held for the first time at RoboCup-2001.

RoboCup Junior Outreach

The RoboCup Junior event hosts children 8-18 years of age who are interested in robotic soccer. The competitions and demonstrations include two-on-two soccer and robot dancing.

Robot Leagues

The real robot leagues, further described in this article, are

- robot rescue
- small-size league
- middle-size league
- Sony legged league.

The Robot Rescue competition was held jointly by RoboCup and the American Association for Artificial Intelligence (AAAI). It was held for the first time as part of RoboCup and it consisted of a disaster scenario provided by the National Institute of Standards and Technology (NIST), where robots navigate among debris to search for victims.

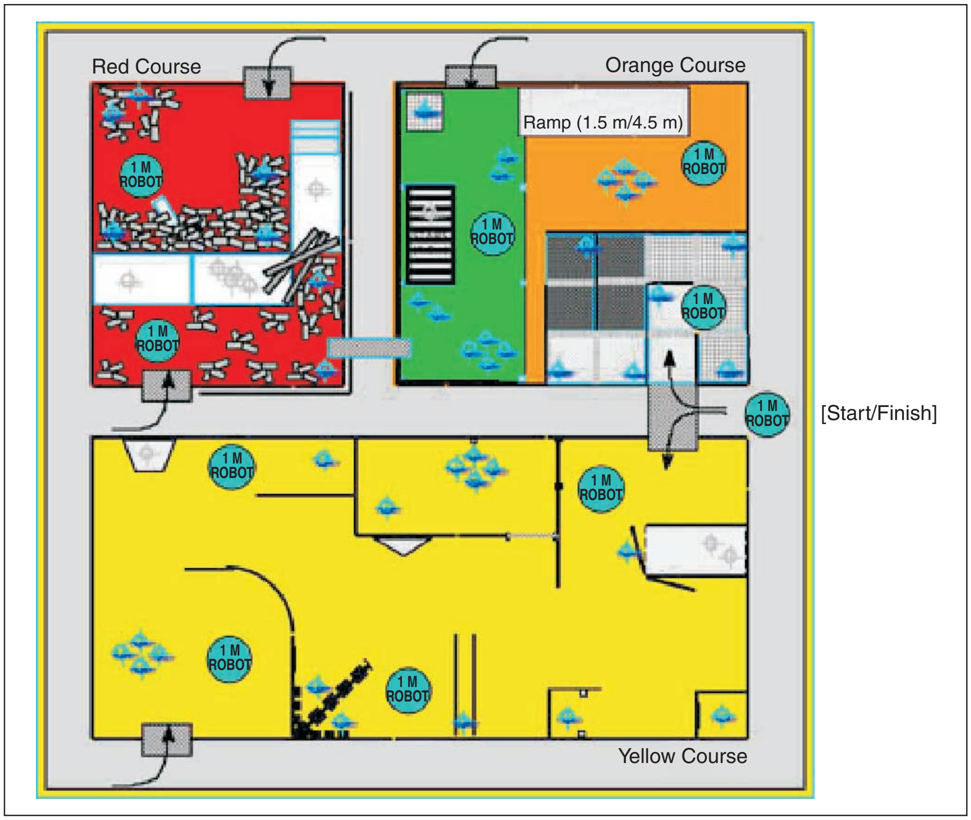

Figure 1. *Diagram of the reference test arena for autonomous mobile robots, the course used for robot rescue (Courtesy NIST).*

RoboCup-2001, jointly with AAAI, held a demonstration of a humanoid. We envision and are planning the first humanoid game for RoboCup-2002.

RoboCup-2001 proved to be a truly significant contribution to the fields of AI, robotics, and sub-areas of multiagent and multirobot systems.

Robot Rescue League

This year's RoboCup Robot Rescue event was held in conjunction with AAAI at the co-located RoboCup and International Joint Conferences on Artificial Intelligence (IJCAI) conferences. This was the first year that the robot-rescue league was part of RoboCup and the second year that the event was held at AAAI. To bring the two communities together, a joint rules committee from RoboCup and AAAI developed the rules and scoring algorithm. There were four registered teams in the competition: Sharif University (Iran), Swarthmore College (USA), Utah State University (USA), and the University of Edinburgh (Scotland). Additionally, several teams demonstrated their robots in the rescue course, including the University of Minnesota (USA) and the University of South Florida (USA).

The robots competed in the reference test arenas for autonomous mobile robots developed by NIST [2], [3]. There are three regions in the urban search and rescue (USAR) arena that vary in difficulty (Fig. 1). The yellow region, with flat floors, is the easiest to traverse. The orange region is more difficult to traverse, with variable floorings, stairs, a ramp, and holes. The red region is the most difficult to traverse, with a very unstructured environment consisting of simulated rubble piles, pancake layers, shifting floors, and hazardous junk such as rebar and wire cages.

The scoring algorithm was designed by the rules committee to address several issues that arise in real USAR situations, including the number of people required to operate the robots (fewer rescue personnel needed to control robots), the percentage of victims found, the number of robots that find unique victims (leading to quicker search times), and the accuracy of victim reporting (best to be as localized as possible). The variables used are as follows

- N, a weighed sum of the victims found in each region divided by the number of actual victims in each region
- C_i, a weighting factor to account for the difficulty level of each section of the arena (C_{yellow}=.5, C_{orange}=.75, C_{red}=1)
- N_r, the number of robots that find unique victims
- N_o, the number of operators
- F, a binary value representing whether an indicated victim is actually present

- V, the volume in which the reported victim is located, given by the operator in the warm zone to the judge
- the average accuracy measure determined by F/V averaged over all identified victims.

A team's score was computed using the following algorithm. (Each team's final score was the best score from four 25-min rounds)

$$\text{Score} = N * \frac{N_r}{(1+N_o)^3} * \overline{A}.$$

No team scored enough points this year to receive a ranking. However, two technical awards were presented. Sharif University received a technical award for advanced mobility for rescue, and Swarthmore University received a technical award for artificial intelligence for rescue. We expect that teams next year will exceed the minimum score necessary for ranking, as both Swarthmore and Sharif were close to meeting the minimum standards this year.

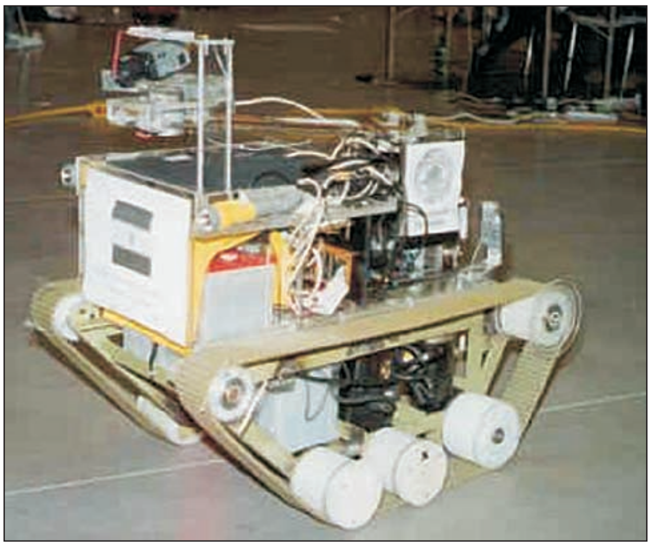

Figure 2. *EMDAD1, Sharif University (Courtesy Sharif University).*

Figure 3. *Swarthmore's robot in the yellow arena, near a victim (Courtesy NIST).*

Sharif University was the only competitor that was able to travel in the orange and red arenas. In the present version of Sharif University's rescue robot EMDAD1 (Fig. 2), the robot is teleoperated; an operator remotely controls the robot through a TCP/IP wireless local-area network (WLAN) and receives images and sounds of the scene the robot is moving on. The software developed for this robot consists of a user-friendly interface; control programs; and simple versions of path drawing and planning, and stereo vision image processing programs. In the next robot version, additional software will be implemented to provide more autonomy for victim detection, collision avoidance, and decision making. EMDAD1's mechanical structure is composed of a track mechanism and a two-degrees-of-freedom (2-DOF) pneumatic manipulator. This structure was designed and fabricated for moving over a 45° slope and passing over obstacles with a maximum height of 10 cm.

Swarthmore College located the most victims of any team operating in the yellow region. Their entry, Mario & Co., consisted of two Magellan Pro robots (Fig. 3). A human operator can either observe or manipulate the robot's activity and switch the robot between autonomous and semi-autonomous modes. The robot is able to detect skin color in an image and provide an estimated location for the sighting based on a ground-plane assumption. The skin-detection module is quickly trainable in real-time, making it adaptable to its environment. In addition, the robot is able to take left and right panoramic images (360°) and build a red-blue anaglyph image of its environment, providing a more realistic perception of the robot's environment to its operator (Fig. 4). Finally, the robots provide important human-readable information about the explored area. The robots build maps using fast evidence grid code. While building the maps, the robots place marker positions on the map that are in known free locations. Upon finding a victim, the robot generates a path from the entrance to the victim by connecting markers that have no obstacles between them.

The Utah State University entry was meant to explore the viability of swarms of inexpensive, simple robots. The robots that made up the Blue Swarm 2 (Blue Swarm 1 was an earlier experiment using analog controls) were modified toy cars using a very simple micro-controller (a BASIC Stamp 2E) running a simple set of rules for interacting with the environment.

Figure 4. *Right 360° panoramic image from Mario (Courtesy Swarthmore College).*

The sensors were limited to bump and infrared (IR) sensors, and there was no communication between the robots. The desired outcome was sufficient coverage of the competition area without the need for detailed rules or for inter-robot coordination. They achieved this outcome but were not scored because they were unable to communicate the location of victims to humans outside the arena. Future plans include a more reliable platform and a method for returning the locations of victims to a rescuer.

The ultimate goal of RoboCup is to reach a point where teams of robots can successfully compete with human players.

The University of Edinburgh robo-rescue team robots were developed as a collaborative master's-degree project. The robots had a three-wheeled aluminum chassis with two dc motors for traction and one dc-modeling servo motor for heat scanning. There are three incremental encoders for dead-reckoning and rotation measurement (one fixed to each wheel); four SRF04-Ultrasonic Rangers (two at the front and one on each side) and two front bumpers (left and right) for obstacle avoidance; one magnetic compass with digital output for positioning; one passive-IR sensor (PIR) for heat detection; and one radio packet controller (RPC) at 418 MHz for communication between robots and the base station. Both robots use Handy boards as the main controller. The robots ran in the yellow region.

We expect to have many more teams participating in next year's event, particularly after recent events. We will once again have a joint rules committee with members from the RoboCup and AAAI communities, and Robot Rescue competitions will be held at both RoboCup-2002 and AAAI-2002.

Sony Four-Legged League

The Sony four-legged robot league started at RoboCup-1998 (Paris) as an exhibition. Three teams, Carnegie Mellon University (CMU, USA), Osaka University (Japan), and Laboratory of Robotics of Paris (LRP, France) were selected and competed with each other. The champion was CMU. In RoboCup-1999 (Stockholm), the league became one of the official leagues of the RoboCup Federation.

The significant feature of the four-legged robot league is that all teams have to use the same hardware developed by Sony. Thus, this is a software competition using physical robots. In RoboCup-1998, we used a prototype of AIBO, and in RoboCup-1999 and RoboCup- 2000, we used ERS-1100, which is a developer's version of AIBO. After RoboCup-2000, we changed our robot platform from ERS-1100 to ERS-2100.

Since 1999, Sony has been organizing the championship competition and the RoboCup challenge. The championship competition is a standard competition soccer game. Each team has three robots, 10 min for the first half, and 10 min for the second half. There is a 10-min break between the first and second halves. Starting from three teams in RoboCup-1998, we have been increasing the number of participants; nine teams in RoboCup-1999, 12 teams in RoboCup-2000, and 16 teams in RoboCup-2001.

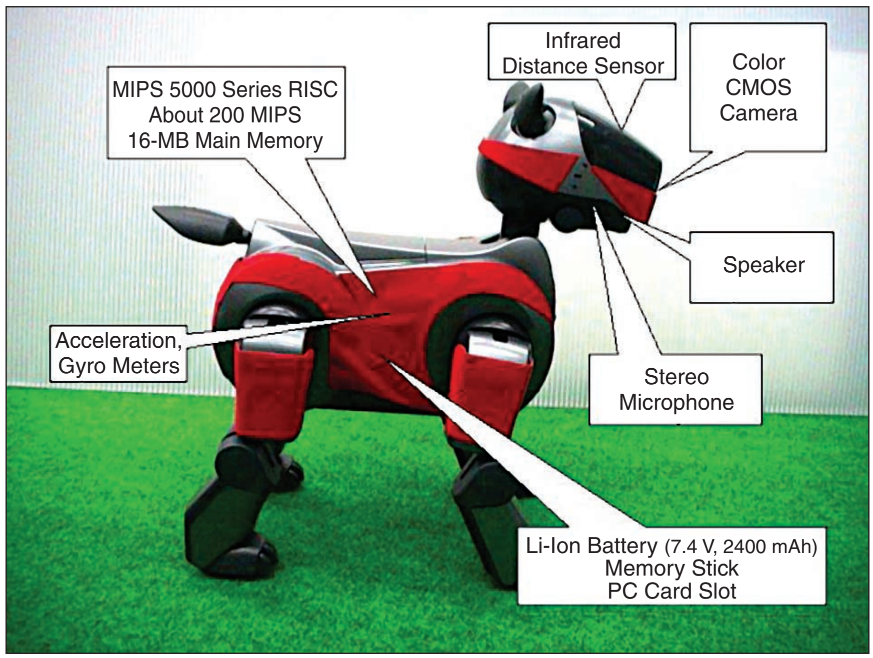

Figure 5. *Robot platform ERS-2100.*

Figure 6. *The color-painted field and overview of the game.*

In addition to the championship competition, every year we continue to hold the RoboCup challenge as a technical routine competition. The challenge focuses on a particular technology more than the championship. For example, through the challenge, we have been evaluating the performance of vision tasks, robot collaboration, etc.

Robot Platform, Field, and Rules

The basic features of the ERS-2100 are almost the same as in the ERS-1100 [4]. The robot is a quadruped and is equipped with a color camera, stereo-microphone, acceleration meters, and gyro meters. CPU power is improved from about 100-200 million instructions per second (MIPS), and main memory is extended from 16-32 MB. Fig. 5 shows the robot platform ERS-2100. Regarding the field, we use the same color-painted setup as in 1998 [4] except that we extend the carpet into the goal area in order to reduce slipping problems for the goalies. Around the soccer field, six color poles (landmarks) are installed that are used for localization of the robots (Fig. 6).

We revised the four-legged robot league rules so that participants try to develop collaborative behaviors. First, we revised the rule about "holding." We allow 3 s of ball holding for field players. With this rule, field players can try to hold the ball, turn to another player or a space in front of a goal, and push (kick) the ball toward this direction. Second, we give a goalie an advantage inside the penalty area, because only one defender (the goalie) can defend inside the penalty area to increase an opportunity of score. The goalie can hold the ball up to 5 s, and attackers can't push the goalie while it holds the ball. If an attacker violates the rule, a referee takes the robot outside of the field for 30 s.

The Competition

In RoboCup-2000 (Melbourne), 12 teams participated in the four legged robot league. In RoboCup-2001 (Seattle), we had selected four more teams so that 16 teams participated in the championship. New teams are: University of Washington (USA), Kyushu United (Kyushu Institute of Technology and Fukuoka Institute of Technology, Japan), Team Balkan [Technical University of Sofia (Bulgaria) and Bogazici University (Turkey)], and University of Science and Technology of China (USTC, China). Note that Team Balkan is the first united team of two countries in this league. The other 12 teams are CMU, LRP, Osaka University, German United (Humboldt University Berlin, University Bremen, University Darmstadt, University Dortmund, Free University Berlin), McGill University (Canada), Team Sweden (Orebro University, Blekinge Tekniska Högskola, Umeå, Sweden), University of New South Wales (UNSW, Australia), University of Pennsylvania (USA), University of Tokyo (Japan), University of Essex (UK), University of Melbourne (Australia), University of Rome, "La Sapienza" (SPQR, Italy).

Until last year, Humboldt University was a representative of Germany, but this year, they formed German United as the national team. Now, we have four united teams in the legged league.

In the first three days, the 16 teams were divided into four groups. Four teams in each group played each other in a round-robin competition, so that the top two teams of each group could go to the quarterfinal tournament. Figs. 7 and 8 show the results of the round-robin and championship tournaments. UNSW came in first place and also won the tournament last year. The second-place winner was CMU, and the third-place winner was the University of Pennsylvania.

There are several comments on the games. First, two of the new participants, USTC and Kyushu United, became quarterfinalists. One of the reasons why new teams can win against experienced teams is our open source-code system. If a team agrees to share the developed source code, the team can use the developed source codes (and documents) from other teams. Kyushu United used the source code of UNSW, last year's champion, and developed their own technology based on it.

Second, robot collaboration has been implemented in a few teams. This year, three teams (UNSW, University of Pennsylvania, and Team Sweden) used sound communication among the robots. For example, the players of UNSW generate sound to signal that a robot is backing off. This strategy has two advantages. The first advantage is that they can avoid blocking each other with the same

A	LRP	ESSEX	Melbourne	USTC	Point	Goal	Lost	Place
LRP		3 - 1	9 - 0	2 - 1	9	14	2	1
ESSEX	1 - 3		1 - 0	1 - 3	3	3	6	3
Melbourne	0 - 9	0 - 1		0 - 1	0	0	11	4
USTC	1 - 2	3 - 1	1 - 0		3	5	3	2

B	CMU	SWEDEN	TOKYO	KYUSHU	Point	Goal	Lost	Place
CMU		12 - 0	5 - 3	8 - 0	9	25	3	1
SWEDEN	0 - 12		0 - 6	1 - 4	0	1	22	4
TOKYO	3 - 5	6 - 0		0 - 5	3	9	10	3
KYUSHU	0 - 8	4 - 1	5 - 0		6	9	9	2

C	S.P.Q.R.	UPENN	McGill	BALKAN	Point	Goal	Lost	Place
S.P.Q.R.		2 - 3	2 - 0	5 - 0	6	9	3	2
UPENN	3 - 2		1 - 0	2 - 0	9	6	2	1
McGill	0 - 2	0 - 1		3 - 0	3	3	3	3
BALKAN	0 - 5	0 - 2	0 - 3		0	0	10	4

D	UNSW	OSAKA	GERMAN	Washington	Point	Goal	Lost	Place
UNSW		8 - 1	11 - 0	12 - 0	9	31	1	1
OSAKA	1 - 8		4 - 1	1 - 0	6	6	9	2
GERMAN	0 - 11	1 - 4		3 - 0	3	4	15	3
Washington	0 - 12	0 - 1	0 - 3		0	0	16	4

Figure 7. *Results of the round robin.*

team robots. The first robot can smoothly reach the ball without any unintentional interference by the teammates. The second advantage is that there are some chances for the waiting robot to get the ball from the crowded place. This often happened in front of the penalty area. The first robot reached the ball at the corner of the field and started dribbling around the goalie. Occasionally, the ball rolled out toward the waiting robot, which then had an easy time pushing the ball into the empty goal.

Third, the walking speed is faster than it was last year. This is mainly due to the new motors of the new robot platform. In addition, many teams could develop stable and fast walking and turning patterns by themselves. In addition, many teams improved the skill of ball control. They investigated many ball-moving methods, such as pushing by the side of the head, pushing by the chest, pushing from holding posture, and so on. These are properly selected and used according to the current situation. For example, if the direction of the body and the goal make a right angle, then pushing by the side head is selected, and if they are in parallel, pushing from holding posture is selected. In a crowded situation, pushing by the chest is useful.

Some teams can recognize if the robot is close to the penalty area and try not to enter the defender's penalty area. Also, some teams can recognize a goalie with the ball in the penalty area, so they wait outside of the penalty area to avoid the goalie charge.

RoboCup Challenges

In RoboCup-2001 (Seattle), we had three different technical routine challenges: 1) goalie, 2) localization, and 3) collaboration. Fig. 9 shows the configurations of these three challenges.

Challenge 1 is to evaluate the performance of a goalie. The goalie is placed on either side of the centerline. After a starting whistle, the goalie has to move to its defense penalty area within 20 s (step 1). After another 10-20 s, the ball is placed on a ramp which accelerates the ball such that it directly rolls to one side of the goal. Then, the goalie has to block the coming ball (step 2) and move it outside of the penalty area (step 3). Three teams, University of Pennsylvania, UNSW, and University of Washington, could complete all the steps of this challenge. University of Pennsylvania took first place in this challenge.

Challenge 2 is to evaluate the performance (speed and accuracy) of localization. The robot is placed on a randomly selected position. There are five markers on the field whose (x, y) information was previously given to each team. Then, starting from the randomly selected position, the robot should visit all markers within 3 min. The markers are not visible to the robot's camera. Therefore, the robot should localize itself by the color landmarks around the field and stop on the known (x, y) positions. Three teams, CMU, UNSW, and Kyushu United were able to visit all markers within 3 min. CMU won first place in this challenge.

Challenge 3 is to evaluate the performance of a passing behavior. Two robots are placed on the penalty line. One robot should play on the right-hand side, the other on the left-hand side. The first robot has to move the ball close to the centerline and pass to the other robot. The second robot should receive and move the ball to the opponent penalty line and pass the ball back to the first robot. Finally, the first robot has to make a goal. Unfortunately, no team was able to complete this challenge.

Overall, UNSW took first place in the RoboCup challenge competition, the University of Pennsylvania took second place, and CMU took third place.

Surprisingly, in the localization challenge, CMU and UNSW could visit all markers in about 1 min. The teams who could visit some markers actually showed very good performance in the championship competition. Thus, localization is an important technology for RoboCup, and many teams could come up with solutions to this problem, which can be implemented in the legged robot field environment.

AI versus Human Control Robots

We gave a demonstration of "AI versus Human Control Robots" during the event. We used a commercially available remote-control software for AIBO ERS-210, whose hardware is almost the same as the ERS-2100. Three robots were remotely controlled by humans, and three were autonomous robots developed by RoboCup teams. We had three games: the human-controlled team versus the University of Pennsylvania, the University of Tokyo, CMU. The human-controlled team was able to beat the University of Pennsylvania and the University of Tokyo teams but was beaten by the CMU team.

Future Research Issues

The technology level of teams in the four-legged robot league has become very high. Specifically, there are many ball-control methods using front legs, head, and body that cannot be observed in the other leagues. Collaborations using sound communication are now available in some teams.

What are the remaining directions for development in this league? One important issue is "environment." At this moment, we need carefully controlled illumination, the color-painted setup, and a flat smooth carpet. We plan to design routine tasks for the RoboCup-2002 (Fukuoka) challenge that aim at investigating some of these problems. In addition, we plan to introduce a wireless LAN (WLAN) system for communication from RoboCup-2002 onward.

Middle-Size League

In the middle-size league (MSL) of RoboCup soccer, teams of four roughly 50 × 50 × 80-cm-sized robots play with each other within a 10 × 5-m field surrounded by walls. No global vision of the field is allowed, hence the robots carry their own sensors, including vision. The robots are fully autonomous, i.e., all their sensors, actuators, power supply, and (in most cases) computational power is on board, and no external intervention by humans is allowed, except to insert or remove ro-

RoboCup continues to drive critical research in multirobot systems, real-time control, sensing, and educational technology.

bots onto or from the field. External computational power is allowed, even though most teams do not use it. Wireless communications among the team robots and/or with the external computer are also allowed. As in most of the other leagues, relevant objects are distinguishable by their colors: the ball is orange, the goals are yellow and blue, the robots are black, the walls are white, and the robot markings (to distinguish the teams) are magenta and light blue.

The Qualification Process

Due to the high number of teams that showed interest in participate in the 2001 edition, all potential participants had to go through a qualification process for the first time in MSL history. Initially, 36 teams (from both academic and industrial institutions) declared their intention to participate. Later, 34 of those preregistered for the MSL. A decision to qualify a maximum number of 27 teams was made based on available space at the competition site.

Team evaluation was carried out by a technical committee of five active RoboCup researchers. The decision on qualification was based on the evaluation of the team description papers, as well as of the team Web page, in order to quantify the following five criteria (listed by their decreasing weight):

1) Mapping of long term scientific goals onto current team status.
2) Robot-development status at evaluation time (from Web videos and pictures).
3) Innovative concepts.
4) Publications concerning related research in journals, conferences, and RoboCup workshops.
5) Student involvement.

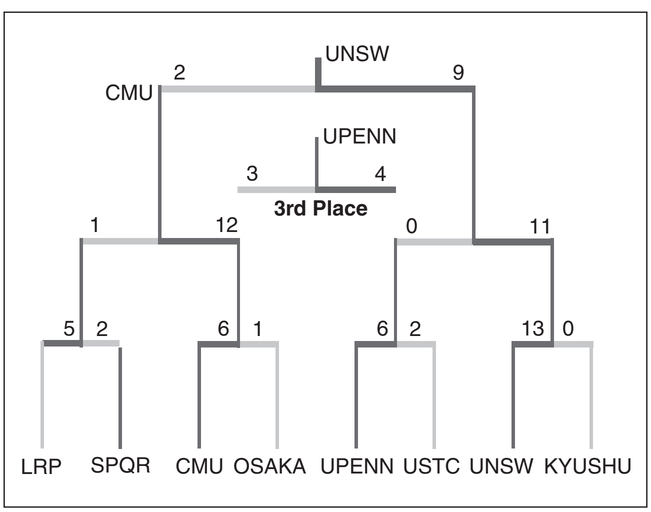

Figure 8. *Results of the championship tournament.*

Team description papers are four-page papers in which teams describe their research goals and technical details of the team robots. They have been used in RoboCup since 1997 as a means to promote the exchange of scientific achievements among participating teams.

Following this process, only 25 teams were qualified and six others were requested to submit videos showing evidence of their capability to participate in the games. Only one of those teams submitted videos within the deadline and was qualified. Nevertheless, by the final registration deadline of 30 June, only 18 teams registered. The other six withdrew, mainly due to problems with their robots. The final 18 teams were (in alphabetical order):

- *Agilo RoboCuppers*, Munich University of Technology, Germany
- *Artisti Veneti*, University of Padova, Italy
- *Clockwork Orange: The Dutch RoboSoccer Team*, University of Amsterdam, VU Amsterdam, Utrecht University, TU Delft, The Netherlands
- *CMU Hammerheads*, CMU, USA
- *CoPS Stuttgart*, University of Stuttgart, IPVR, Germany
- *CS Freiburg*, University of Freiburg, Germany
- *Eigen*, Keio University, Japan
- *Fun2maS*, Politecnico di Milano and Universita degli Studi di Milano-Bicocca, Italy
- *Fusion*, Kyushu University, Hitachi Information & Control Systems, Inc., Fukuoka University, Japan
- *GMD Robots,* GMD German National Research Center for Information Technology, Germany
- *ISocRob*, Instituto de Sistemas e Robótica—IST, Lisbon Technical University, Portugal
- *JayBots*, John Hopkins University, USA
- *Minho Team*, University of Minho, Portugal
- *RoboSix*, Pierre & Marie Curie University (UPMC—PARIS VI), France
- *Sharif CE*, Sharif University of Technology, Iran
- *SPQR*, University of Rome "La Sapienza," Italy
- *The Ulm Sparrows*, University of Ulm, Germany
- *Trackies*, Osaka University, Japan.

The Competition

The actual RoboCup-2001 MSL competition took place from 2-10 August in Seattle. The 18 teams were split into three groups of six teams each, based on a draw made on site in the presence of all the team leaders. There was one MSL field per group, so the games occurred simultaneously in the three groups (Fig. 10).

The first two days (2 and 3 August) were left for the teams to set up. This is the usual procedure at RoboCup, since the robots must be unpacked, and their systems (especially color segmentation) must be calibrated for the competition site conditions. Often, unpacking brings sad surprises, as the robots may need repair after transportation hassles. All these procedures, including the unfortunate ones, can actually be seen as part of the participation process, as a team must prepare to face all difficulties by assigning different responsibilities to its team members and be ready to respond quickly to onsite difficulties.

In the initial competition stage, the six teams in each group played with all the other five opponents in a round-robin tournament. The teams had to make sure that their batteries were ready to support two games of 20 min each per day, with a 10-min break in the middle of each game. The first two teams in the final classification of each group were qualified to the finals stage, together with two out of the three third-place teams. The latter were selected based on the scores of a short round-robin tournament between those three teams. The finals stage was composed of quarter-finals, semi-finals, third- fourth place match, and final match in two days (9 and 10 August). In each match, the defeated team left the competition.

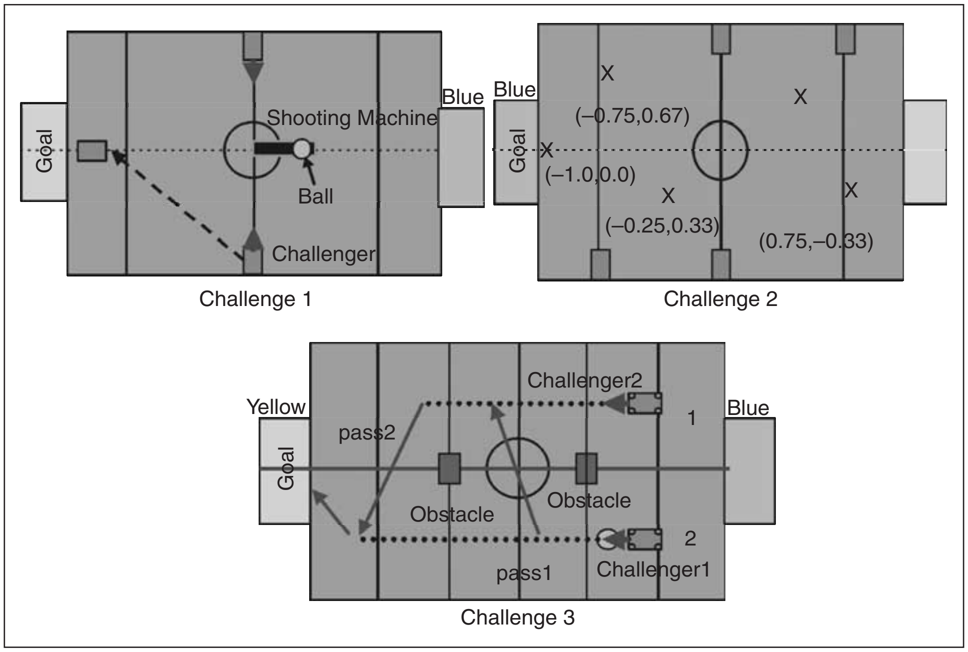

Figure 9. *Configuration of three RoboCup challenges.*

CS Freiburg was, for the third time in MSL history, the winner of the 2001 edition, after defeating Trackies 1-0 in the final. The scores of the finals stage are listed in Table 1.

Research Issues

The 2001 edition of the RoboCup MSL taught some lessons to the participating teams. Perhaps the most important one is that reaction speed is becoming a vital feature that every team should display. In the past, a slow but perception-wise effective team would be able to defeat faster but behavior-wise "chaotic" teams. Currently, the best teams are simultaneously fast and effective when pursuing the ball or, after gaining its possession, when dribbling past opponents while pushing the ball towards the goal. So, the need to *plan* and/or *react* faster under an increasingly dynamic adversarial environment has become even more stringent than ever.

Most teams are using a behavior-based approach to their robots' functional design, based on software running on the Linux operating system. The behavior-based approach has fostered research on several topics that contribute to different behaviors, such as navigation, path planning, object pushing, mechanical kicking devices, to name but a few. Some enabling methodologies also had to be applied to this environment, such as sensor fusion, color segmentation, or omnidirectional vision. Multithread software architectures are becoming a standard to support concurrent behaviors, one of them selected at a time, based on their potential performance given the current world state and/or upon the occurrence of specific events. Some teams use a world model distributed over the team robots, while others centralize the world model in an external computer capable of exchanging information through wireless ethernet with the team.

Absolute self-localization has become an almost standard feature of every team in the MSL, using either laser range finders or vision sensors and field natural landmarks (e.g., the walls, the field lines, the goals). A robot that knows its position in the field can make decisions on where to move and what to do next more quickly. Nevertheless, some teams prefer to use a "relative localization" approach, where decisions are made based on the relative locations of the robot, ball, goals, and opponents. A mixed solution [where absolute self-localization is performed periodically or after events that may disturb odometry (e.g., after bumping into another robot), but relative localization is preferred once the robot can see the ball and the goal] is becoming popular, partly because vision-based absolute self-localization is still not very robust.

Some issues, recurrently discussed by the community, are becoming increasingly clear. Removing the field walls to expose the robots to a more realistic scenario, where relevant objects will have to be more robustly detected, is one of them. However, this step may also create the need to face other challenges: better ball manipulation, requiring manipulating devices, and automatic refereeing, so that the robots respond to referee decisions (such as repositioning a ball leaving the field) in an autonomous and quick manner. The community feels a strong need to increase the autonomy and reliability of the robots, so that human intervention is reduced to a minimum.

The greatest challenge is to try to come up with design methodologies (if possible, driven by specifications) for behavior coordination, as well as for behavior distribution per teammates, so that real teamwork is displayed and proves to be

RoboCup is growing, both in terms of participants and in terms of competition events.

superior to more individualistic actions, such as those currently seen during the games.

Small-Size League

In the RoboCup small-size league, five robots with a maximum diameter of 18 cm play against each other. A camera mounted above the field is connected to a computer that processes each frame in order to find the robots and the ball. One team has a blue marker on the top of its robots, the other team has a yellow marker. The ball is orange. The field is covered with a green carpet.

The robots in the small-size league are not fully autonomous, since the external computer compiles all the information about the state of the game and transmits the necessary commands to every robot. However, most teams treat each robot as an individual agent and the amount of shared information is minimal.

The challenge in the small-size league is to build a system that is robust in four different ways:

- *Mechanically:* The robots should withstand hard collisions.
- *Adaptive computer vision:* The computer vision system should be able to deal with gradual changes in lightning and shadows.
- *Fault-tolerant wireless links.*
- *Adaptive control behavior:* The robots in the small-size league are much faster, relative to the field size, than the robots in the mid-size league. Speeds of 1-2 m/s are not uncommon, while the field has a maximum side length of 2.7 m. The challenges associated with this league are the exact control of very fast robots, navigating around fast moving obstacles, and playing with high fault-tolerance.

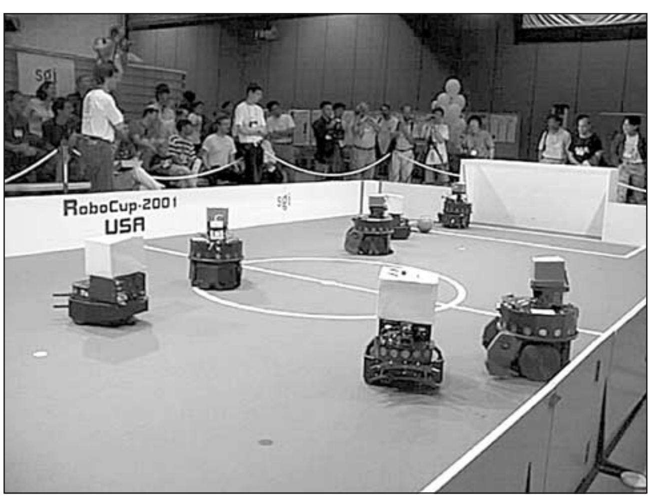

Figure 10. *MSL quarter-final game between Agilo RoboCuppers and CoPS Stuttgart (Courtesy of U. Minho).*

In Seattle, of the 23 teams that participated in the small-size league, four were local-vision teams (i.e., with an on-board camera). The teams played the round robin in four groups and the playoffs with eight qualified teams. The list of participating teams, including a reference to those who used local vision, includes

- *Team Canuck*, Canada
- *Cornell Big Red*, USA
- *RoGi Team*, Spain
- *Roobots*, Australia
- *Sharif CESR*, Iran
- *Field Rangers*, Singapore
- *FU-Fighters*, Germany
- *Owaribito*, Japan
- *Robosix*, France
- *Viperoos* (Local Vision), Australia, sharing games with *FU-Fighters-Omni* (Local Vision), Germany
- *5dpo*, Portugal
- *Huskies*, USA
- *Lucky Star II*, Singapore
- *OMNI* (Local Vision), Japan
- *WHH-Cats*, Taiwan
- *4 Stooges* (Local Vision), New Zealand
- *CM-Dragons-2001*, USA
- *KU-Boxes-2001*, Japan
- *RoboRoos-2001*, Australia
- *TPOTs*, Singapore
- *ROGI*, Spain.

The winner of the small-size league was Lucky Star II, a team from Singapore. Second-place went to the Field Rangers, also from Singapore, and third-place went to Cornell University, last year's small-size champion.

The Cornell team generated much attention because their robots use a dribbler (a rotating bar) capable of rotating the ball against the robots. The ball sticks to the robots but can also be kicked using a linear magnet. The Cornell team showed a team capable of passing the ball around the field in a controlled fashion. Especially impressive was the pass-and-kick technique they showed: a robot passes the ball to another that is already positioned for a direct shot to the goal line. On receiving the ball, the second robot triggers its kicking device. The Cornell team could score many goals using this technique.

Lucky Star II, a team that had been unlucky the last two years, finishing third in 1999 and 2000, could profit from their great robot control at last. Although they do not employ an omnidirectional motion system (three wheels) like other teams, they can drive the robots in a very precise way. No team was capable of scoring against Lucky Star during the whole tournament, a feat that had escaped all other winners of this league in previous years.

The last two games, Lucky Star against Field Rangers and Cornell against the FU-Fighters, were very exciting. The latter game ended 6-5 and was decided by a penalty shot 20-s before the end of the game.

The general level of play has increased during the last two years. The eight qualified teams for the playoffs have good computer vision, control, and mechanics. The difference in quality between the best eight teams has been steadily decreasing in the last two years.

One important issue this year was the development of fully autonomous robots, like in the MSL, that have their own cameras and vision systems. Four teams showed local-vision systems in Seattle, and one of them, the FU-Fighters Omnivision, won the local-vision derby. This team is as good as the best global-vision teams of 1998, so it can be expected that, in 2004, local-vision teams will be playing as well as today's best global-vision teams.

It was agreed after the Seattle tournament to increase the size of the field of play to around 2.8 × 2.4 m in order to increase the strategy level used by most teams.

Conclusion

RoboCup continues to drive critical research in multirobot systems, real-time control, sensing, and educational technology. Additionally, and quite importantly, it continues to motivate and inspire hundreds of students to research in computer science, robotics, and multiagent systems. The scientific results originating in RoboCup have broad impact on robotics and computer science, especially with regard to problems in real-time sensing, acting, and reasoning [5].

RoboCup is growing, both in terms of participants and in terms of competition events. This year, RoboCup added a new competition, Robot Rescue. Robot Rescue includes research on aspects of human control of multirobot systems that are not addressed in other competitions. Robot Rescue also provides a means for researchers to demonstrate how robotic, human-robot interfaces, and robot team technologies can have an immediate, positive impact on society.

We anticipate continued growth and even more exciting research to be displayed and reported at RoboCup-2002, to be held in Fukuoka, Japan. RoboCup-2002 will include several firsts. Several teams will participate in soccer games of 11 versus 11 robots (22 robots in all). Also, RoboCup will include humanoid robot competition for the first time.

Acknowledgments

The following people contributed descriptions of their rescue robot entries: Amir Hossein Jahangir (EMDAD1, Sharif University), Bruce Maxwell and Edward G. Jones (Mario & Company, Swarthmore College), Dan Stormont (Blue

Table 1. Scores of the final stage of RoboCup-2001 MSL.

9 August			9 August			10 August				
9-10	CS Freiburg	4								
	Clockwork Orange	0		CS Freiburg	2	Final				
			15-16				CS Freiburg	1		
10-11	Agilo RoboCuppers	0		CoPS Stuttgart	0					
	CoPS Stuttgart	1								
						11:30-12:30			CS Freiburg	First
11-12	Trackies	4								
	Fusion	2		Trackies	3					
			16-17				Trackies	0		
12-13	Eigen	3		Eigen	0					
	GMD Robots	2							Trackies	Second
						Third-Fourth Place				
							CoPS Stuttgart	0		
						9-10			Eigen	Third
							Eigen	3		
									CoPS Stuttgart	Fourth

Swarm 2, Utah State University), and Jesus Juarez-Guerrero, Ioannis Pissokas, and Daniel Farinha (Robo-Rescue Team, University of Edinburgh).

Keywords

Autonomous robotrs, RoboCup, humanoid robots.

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