RoboCup Soccer Leagues

Daniele Nardi, Itsuki Noda, Fernando Ribeiro,
Peter Stone, Oskar von Stryk, Manuela Veloso

■ *RoboCup was created in 1996 by a group of Japanese, American, and European artificial intelligence and robotics researchers with a formidable, visionary long-term challenge: By 2050 a team of robot soccer players will beat the human World Cup champion team. In this article, we focus on RoboCup robot soccer, and present its five current leagues, which address complementary scientific challenges through different robot and physical setups. Full details on the status of the RoboCup soccer leagues, including league history and past results, upcoming competitions, and detailed rules and specifications are available from the league homepages and wikis.*

RoboCup was created in 1996 by a group of Japanese, American, and European artificial intelligence and robotics researchers with a formidable, visionary long-term challenge: By 2050 a team of robot soccer players will beat the human World Cup champion team. At that time — the mid 1990s — there were very few effective mobile robots, and the Honda P2 humanoid robot had just been presented to the public for the first time. The RoboCup challenge, set as an adversarial game between teams of autonomous robots, was therefore a fascinating and exciting development as well as a reference problem for AI.[1]

RoboCup introduced three robot soccer leagues, Simulation, Small Size, and Middle Size, and organized its first competitions at the 1997 International Joint Conference on Artificial Intelligence, held in Nagoya, Japan. It had a surprisingly large number (100!) of participants. From those modest

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beginnings grew what has become a large, vibrant research community that continues to grow. RoboCup soon established itself as a structured organization — RoboCup Federation[2] — that sponsored annual competition events where the scientific challenges faced by the researchers are addressed in a setting that can be viewed by the general public. RoboCup events have now become quite popular both with the general public as well as the research community. The events now also include a technical symposium featuring contributions that are relevant to the RoboCup competitions and beyond.

In addition to robot soccer, RoboCup has begun addressing concrete challenges faced by society. Since 1999, for example, RoboCup Rescue (Sheh et al. 2012), motivated by the difficulties faced after the Kobe earthquake in 1997, has been addressing the development of robots to support search and rescue operations. In 2006, RoboCup@Home (Wisspeinter et al. 2009) began focusing on human-robot interaction and the development of useful robotic applications that can assist humans in everyday life. Recently, RoboCup had begun addressing industrial domains: the competition RoboCup@Work is at a preliminary stage. The Logistics League, a new league sponsored by Festo (a global manufacturer of pneumatic and electromechanical systems, components, and controls for process control and factory automation solutions), was introduced in 2012 to address abstract factory logistics. Finally, since 2000, RoboCup Junior has provided students up to the age of 19 with a new and exciting way to understand science and technology.

The RoboCup Federation organizes a single yearly international event (RoboCup 2014 was held in João Pessoa, Brazil, July 21–25) that attracts more than 1500 participants and features nearly 200 teams in the major leagues. RoboCup has a broad international participation, with teams joining from more than 40 countries worldwide. As the number of RoboCup researchers grows over the time, RoboCup has had to limit participation to a fixed number of competing teams per event. Consequently, researchers also organize regional communities and events, several of which now equal the size of the main international event.

In this article, we focus on RoboCup robot soccer, and present its five current leagues, which address complementary scientific challenges through different robot and physical setups. Full details on the status of the RoboCup soccer leagues, including league history and past results, upcoming competitions, and detailed rules and specifications are available from the league homepages and wikis.[3] The proceedings of the annual RoboCup Symposia (published by Springer Verlag)[4] provide a large collection of research achievements in all the RoboCup leagues. Additional reports on RoboCup events have appeared in *AI Magazine*.

The Simulation League

The Simulation League is a competition of virtual soccer agents (robots). The physical level simulation as soccer-playing robots is simplified and abstracted so that researchers can focus on developing strategic-level intelligent agents that realize cooperative behaviors. Currently, this league consists of two subleagues, the 2D League (two-dimensions) and the 3D League (three-dimensions), separated according to the abstraction level of the physical simulation.

The 2D subleague involves a game of two teams with 11 players using the FIFA World Cup's full-size 2D soccer field. A player is modeled as a circle with two facing directions (body and head), and can do turn, dash, kick, and turn-head as basic actions. So the agent program needs to dynamically generate suitable sequences of these actions according to each situation.

The 3D subleague uses a more realistic model of robots based on Aldebaran's Nao, which can act in a 3D space. Players' actions are motor commands to each joint of the body. Hence, controlling the motion of the robot becomes more challenging than in the 2D subleague.

In recent years, the Simulation League — especially the 2D subleague — has become a game of strategies rather than of individual skills or team tactics. In the early stage of the Simulation League, the participants focused on the development of skills to control each player and gain better ball handling and motion planning, as in other physical robot leagues. Participants have thus addressed team tactics like positioning of players and role assignment and adaptation and learning methods to adjust pass plans among multiple players. While this capability still presents several challenges, several teams have also started working on the strategic game-plan level, in which they change their play styles and formations according to the opponent performance during a game. This change means that dynamic opponent modeling is now required to build a winning team. In the near future, deep planning and learning methods to model opponents and fool the opponent's analysis are expected to emerge.

Separation among levels of strategy, tactics, and skills is not trivial, and the architecture still raises interesting open issues. However, to encourage researches on more strategic planning and learning, the Simulation League has adopted the coach agent system. A coach agent can observe all movements in the field and can communicate with player agents at restricted times, for example during out-of-play. As a consequence, the coach agent can make a team-strategic decision and control team tactics according to the game situation. This means that participants need to think about how to divide the control of the game between coach and players.

The Simulation League has been used as a test bed to measure performance of learning and representation of teamwork (collaborative behaviors of multia-

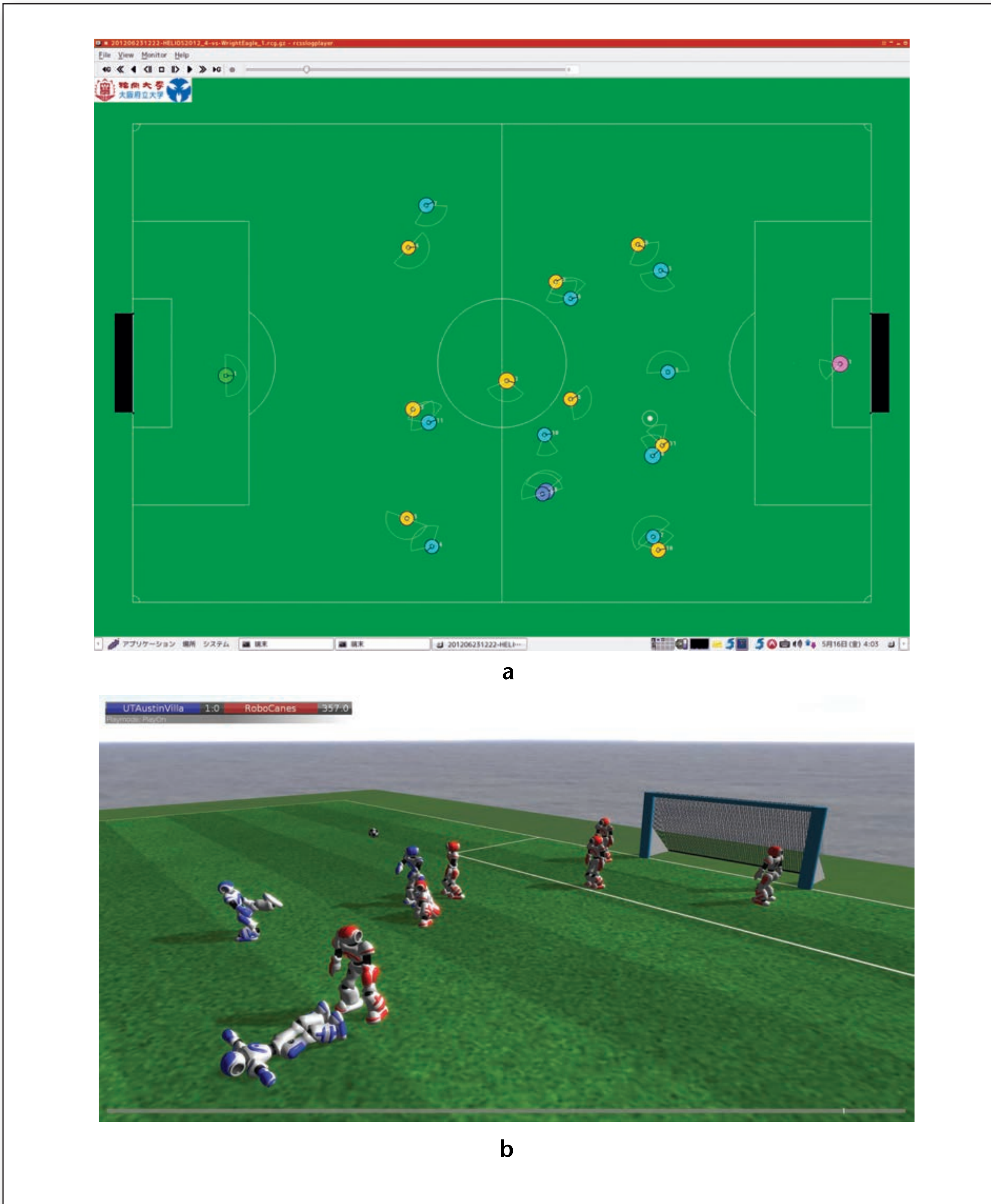

Figure 1. The Simulation League.

(a) 2D simulation. (b) 3D simulation.

gents). For example, the ability to transfer learned behavior from simple tasks to complex ones in multiagents was shown by using the framework of the Simulation League. Because soccer as a multiagent game is a complex problem, the design of teamwork in the Simulation League is an outstanding research challenge that can be addressed by applying incremental and iterative methods like machine learning.

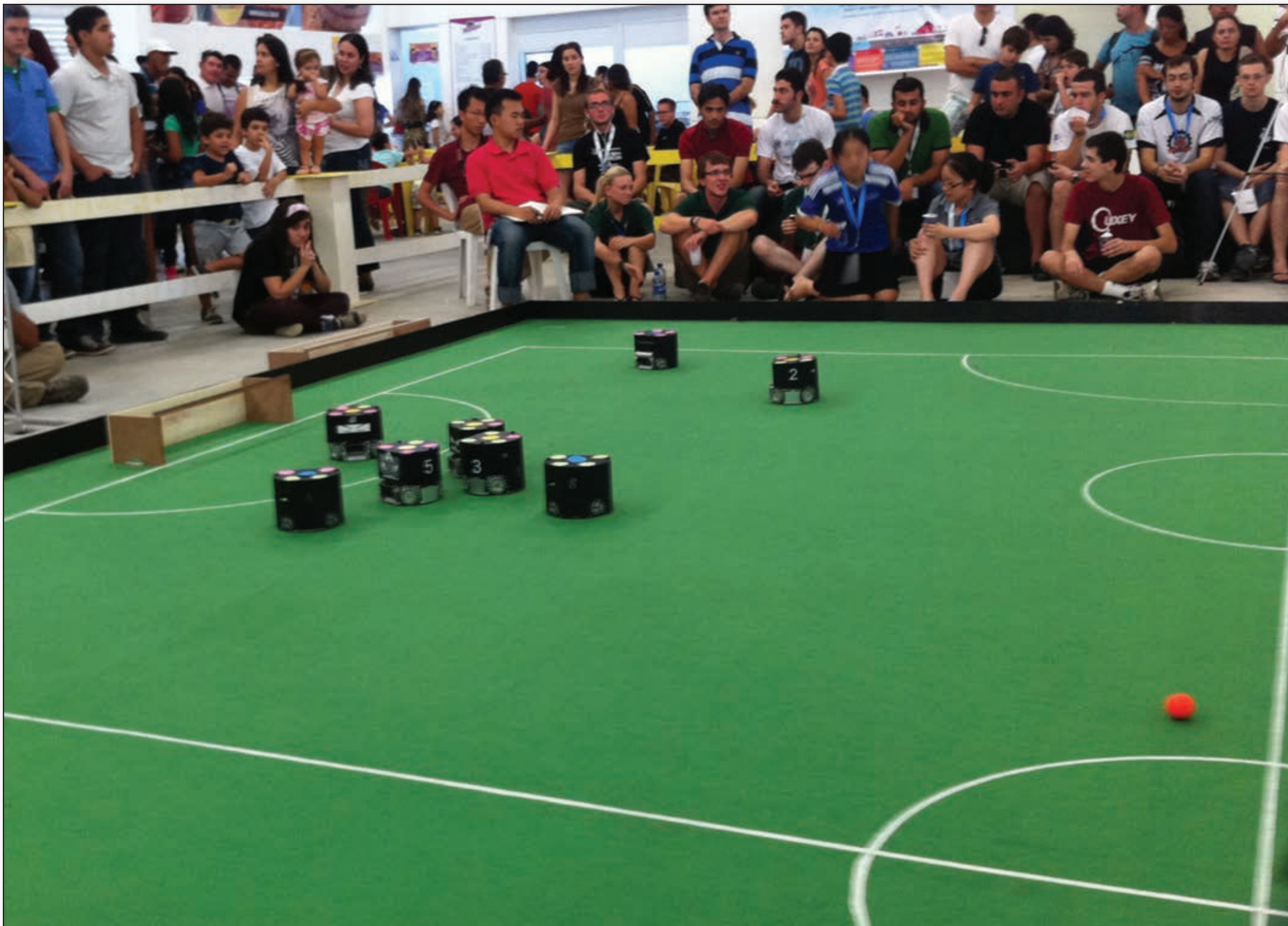

Figure 2. The Small Size League.

The Small Size Robot League

The RoboCup Small Size Robot League consists of a specific organization in which two teams of small robots compete against each other under three core assumptions: (1) robots may be built by researchers only under a size restriction, that is, there are no constraints on any other aspects of the robot hardware such as weight, cost, materials, or capabilities like kicking devices; (2) a central vision system may be used to perceive the complete playing field, and (3) robots may receive motion commands remotely from an external computational, nonhuman, source.

The RoboCup Small Size League was one of the first three leagues of RoboCup. Like all the other leagues, the technical challenges faced by the participants have increased every year. The size of the field, once the size of a ping-pong table, will, for 2014, be 12 by 8 meters with corresponding line markings and goal sizes. The playing ball is an orange golf ball. The number of robots per team has increased from 3 to 6. Each robot must fit within a 180-millimeter-diameter circle and be no higher than 15 centimeters. All the teams converged in choosing to use the allowed centralized perception and computation, and the league evolved to a common robot marking system, now processed by a common vision system, SSL-Vision, whose output is then shared with all the individual team computers. The SSL-Vision is open source, created and maintained by the league's community, and can be configured to be used beyond the specific Small Size League setup.

A common computer is used to communicate referee commands and position information to the team computers. After initial manual robot setting at game stoppage events, the robots completely autonomously process all referee and game calls by positioning themselves; typically, most, sometimes all, of the processing required for coordination and control of the robots is performed on external computers.

Figure 3. The Middle Size League.

Robot hardware design is still a challenge, because of the size restrictions and of the new sensing capabilities that become possible on-board the robots. Nonetheless, perception is essentially solved by the external vision system, thus the scientific focus of the Small Size League is on robot control: the speed of the robots as well as of the ball is very fast; moreover, the capabilities of the players in dribbling, interception, and shooting are remarkable, and typically achieved through machine-learning approaches. However, the teams compete mostly at the strategic level, using positioning, passing, and high-level decision making. Sequences of multiple passes and complex plays have become commonplace. Machine learning is applied also in many high-level tasks: a unique example of learning the opponents' behaviors and strategies in real robot systems has been shown in this league.

The Middle Size Robot League

In the RoboCup Middle Size League two teams of five robots play on a green 18 by 12 meter indoor carpet field with white lines (similar to a real football field) and 2 by 1 meter net goals. Robots may be no more than 80 centimeters in height, 50 centimeters in diameter, and may weigh no more than 40 kilograms. The robots are equipped with a computer to process acquired data and use several sensors — all of which must be on the robot itself (no external sensors are allowed). The robots play football autonomously, using a wireless network to communicate among themselves. They also communicate with an external computer, which receives instructions from a referee through a referee box, but all sensing and computation is done on board.

No external intervention by humans is allowed in the game, except to remove robots from the field should they break down. Consequently, the robots are totally distributed and autonomous. Robots recognize objects and localize themselves using sensor information, they decide which action to take, and they control the motors and actuators autonomously accordingly. Matches are divided in two 15-minute halves.

This Middle Size League has had major achievements during the last few years. Middle Size League teams have developed software that allows amazing forms of cooperation between robots. The passes are very accurate and some complex, cooperatively made goals are scored after passing the ball, rather than just out-dribbling an opponent and playing individually.

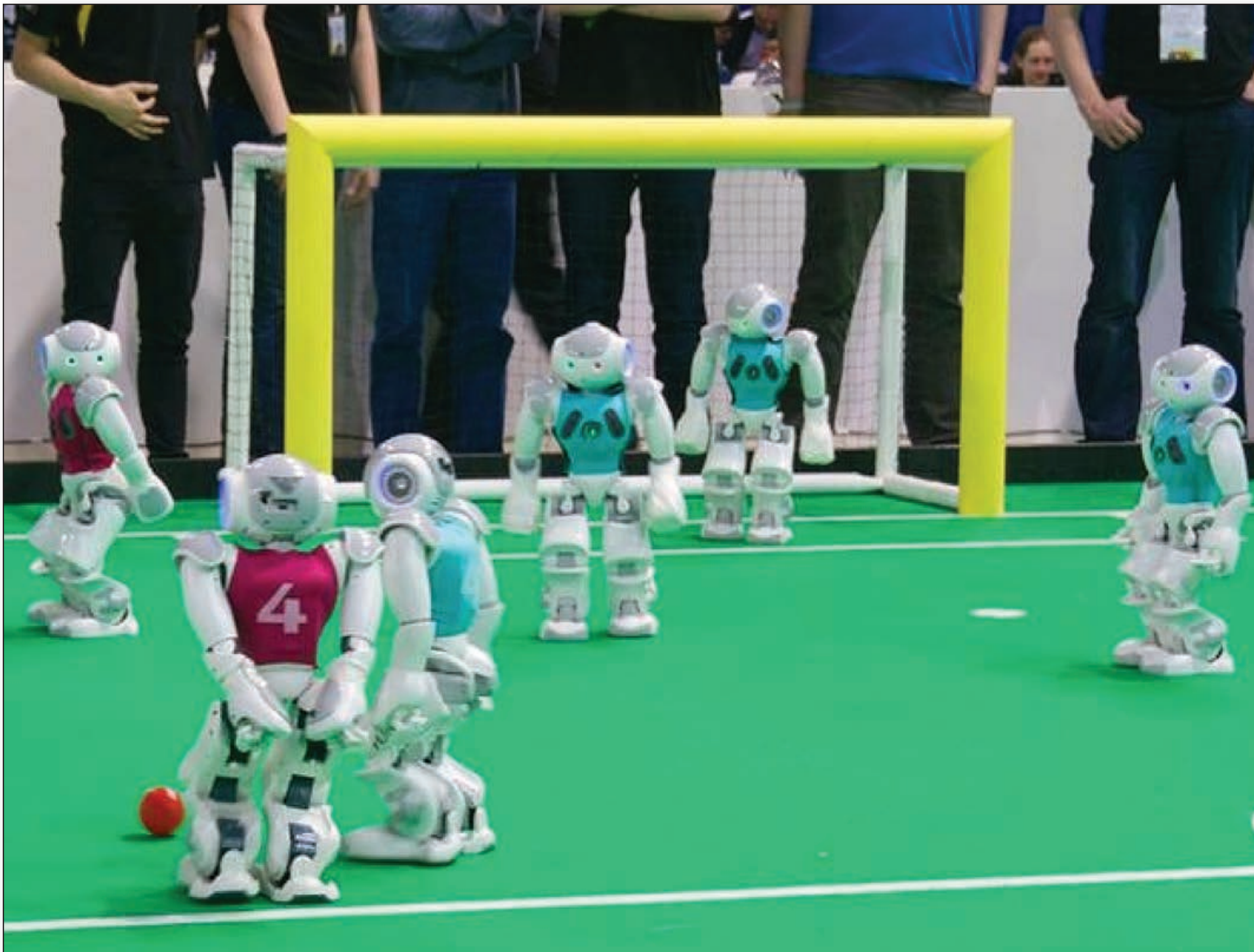

Figure 4. The Standard Platform League.

The Middle Size League removed colored goals some years ago, including colored corner posts, the large fences around the field, as well as special lighting. The ball can now be of any color, and teams are allowed only a few minutes to show their robots the ball that will be used. The speed of the robots, while maintaining ball control, is impressive. Velocities of up to 3 to 4 meters per second are easily achieved, thus requiring suitable control techniques. The robots also use dribblers, which are devices that are able to minimally control the ball without dragging it on the floor (the rules clearly state that the ball must roll free). The ball does not always move on the floor, since most teams have developed kicking mechanisms that allow upward ball kicking, thus making the game more similar to the game humans play. Although the kicks can be so strong that the ball could be propelled from one goal to the other, the rules forbid such plays and encourage the development instead of cooperative behaviors to score goals. The robots from this league have been able to play games with humans since 2007, and a human-robot game now happens every year to test the progress achieved by the robots.[5]

Several challenges related to motion and perception have been solved in this league during its existence, leading to very effective omnidirectional mobile platforms and vision systems. The current capabilities of the robots allow teams to focus on cooperation and strategy, but a new playing field that features artificial grass is being developed, which might require substantial innovation in the overall design.

The Standard Platform League

Of the three original leagues introduced in 1997, two of them required teams to design and build their own robots (the Small Size and Middle Size Leagues), while one reduced real-world complexities to abstractions (the Simulation League). The Standard Platform League was introduced to provide an avenue for participants to work with real robots but without the need to design and build their own.

Originally called the Four-Legged League because of its use of the Sony Aibo robot, the Standard Platform League added the new challenge of legged locomotion (previously, robots all moved on wheels). The Standard Platform League began with a three-team demonstration in 1998, and the league was fully launched in 1999. The Aibo continued as the standard platform until it was discontinued in 2007. After an open competition that year, the two-legged (humanoid) Aldebaran Nao robot was adopted as the standard platform beginning in 2008. It continues to be so to the present day. Games are currently played among teams of five robots each on a 6 by 9 meter field.

All sensing and computation has always been required to be performed on board the robot. Interrobot communication is allowed either through sound or through a wireless access point with limited bandwidth. The main sensors are cameras located in the robot's head, with limited fields of view. Thus the technical challenges have included real-time processing of high-resolution color-based images, and active reasoning about where on the field the robot should focus its attention. For example, constantly focusing on the ball's location may be at odds with looking around to notice where other robots are located or to self-localize.

The self-localization challenge in this league has gradually evolved from different-colored goals and six uniquely patterned beacons placed at known locations around the field, to two goals of the same color with no field markings other than white lines. Thus robots are now faced with the challenge of determining which direction on the field they are facing on a fully symmetric field. They can do so at first by tracking their movement over time from a known starting position (for example, by using a Kalman or a particle filter). However, especially if they fall near midfield, there is significant risk of becoming disoriented when they stand back up. One solution to this problem has been communication of the ball's location among the teammates as a way of breaking the field's symmetry.

Speed and robustness of robot locomotion and speed and power of kicking have been important differentiators in this league. Teams with fast-moving robots have a large advantage. However, strategy and teamwork, including where to kick the ball, and where robots without the ball should position themselves, have also played important roles.

Figure 5. Humanoid TeenSize League.

The most recent addition to the Standard Platform League has been a new drop-in player challenge that tests robots' abilities to cooperate with previously unknown teammates in an ad hoc teamwork setting (MacAlpine et al. 2014).

The Humanoid Robot League

At the beginning of the Humanoid League in 2002, participating humanoid robots were quite diverse. Sizes ranged from 10 up to 220 centimeters. The early competitions focused on basic abilities like walking, standing on one leg, and on penalty kicks. Performance factors were applied to account for the diversity among robots. Today robots compete in three different, well-established size classes on a 6 by 9 meter field. In KidSize (40–90 centimeter height) teams compete with four players per team and in TeenSize (80–140 centimeter height) with two. In AdultSize (130–180 centimeter height) one striker robot plays against a goalkeeper robot first and then the same robots exchange roles and again play against each other. In parallel to the soccer games, technical challenges are run as separate competitions that address specific individual robot (like throw-in, dribbling around obstacles) and team skills (such as multiple double passes) required to advance research and development of humanoid soccer robots.

With its focus on autonomous robots with humanlike body senses, the league has a unique profile in humanoid robotics. Perception and world modeling have to cope with humanlike external sensing. For example, vision must be restricted to a humanlike limited field of view and hearing must also be humanlike. Teams are not allowed to use the popular, nonhumanlike active range sensors. Another significant aspect of humanlike embodiment is the restriction of foot size with respect to the height of the center of mass, thus requiring teams to deal with the dynamics and stability of walking. To cope with high uncertainty in perceiving the state of the world, a humanoid robot must be able to coordinate visual perception with body motions to search for and track objects properly, all the while planning and performing versatile bipedal locomotion that minimizes the likelihood of falls.

In 2002, almost all robots struggled with basic locomotion capabilities like standing on one leg, walking, and kicking. Nowadays teams have been able to successfully deal with the strict requirement for humanlike body plan and senses. Teams of autonomous humanoid robots in the KidSize and TeenSize classes now perform fast and exciting soccer games and execute many goals. Some of the best autonomous humanoid robots in the world, featuring the most versatile and robust motion abilities, regularly compete in the Humanoid League.

Since 2002, the Louis Vuitton Humanoid Cup, a crystal globe crafted by Baccarat, has been awarded to the overall best humanoid robot. The award-winning team is entitled to hold the cup for a year until the next RoboCup World Championship event. Since 2006, an annual workshop dedicated to the scientific challenges and progress in humanoid soccer robots has been held at the annual IEEE-RAS International Conference on Humanoid Robots. Collections of papers from the Humanoid League have appeared as special issues in various publications.[6]

Conclusion

The RoboCup Symposium is a scientific venue where researchers present their technical solutions to the scientific community. The proceedings of the RoboCup Symposium have been published annually since 1997; furthermore, contributions arising from RoboCup research and practice consistently appear in a variety of forms, including master's theses and Ph.D. dissertations, as well as the many other publications in the AI and robotics field. RoboCup offers significant soft-skill training for young researchers working together in teams to achieve a common goal in a limited time frame. Despite the competition framework, all participants enjoy a very open, cooperative, and enthusiastic atmosphere and unique experience. As a consequence of these achievements, RoboCup has become one of the main international events in the field of artificial intelligence and robotics, and its impacts are felt in science, education, and society.

The robot Quince from RoboCup Rescue was deployed during the rescue operations in the Fukushima-Daiichi Nuclear Power Plant. Kiva Systems has revolutionized automation by using hundreds of mobile robots to store, move, and sort inventory. One of the company's technical founders was a successful RoboCup researcher. Research labs in robotics now recognize Aldebaran Robotics' NAO robots worldwide. The company's robots were introduced and selected at RoboCup 2007 as a standard robot soccer platform.

The success and achievements of RoboCup have been supported by the RoboCup Federation's ability to continuously consider new challenges and revise the rules and conditions of each of its leagues in response to the technical and scientific accomplishments and interests of the research community, while not straying from its ultimate goals.

Notes

1. See the video clip by Herbert Simon on Robot Soccer, Forecasting the Future or Shaping It? October 2000, www.youtube.com/watch?v=nCy4-Wgtay8.

2. See www.RoboCup.org.

3. See wiki.robocup.org.

4. See *Robot Soccer World Cup* I–XVIII, published by Springer Verlag from 1998–2014.

5. See Soccer Robots Score on Humans at RoboCup: GOOOOOOAL! by Evan Acerman (Posted 30 July 2014) in *IEEE Spectrum* (spectrum.ieee.org/automaton/robotics/diy/soccer-robots-score-on-humans-at-robocup).

6. See, for example, the special September 2008 issue on humanoid soccer robots in the *International Journal of Humanoid Robotics* 5(3) and the July 2009 special issue on humanoid soccer robots in *Robotics and Autonomous Systems* 57(8).

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Daniele Nardi is a full professor of artificial intelligence at the Sapienza University of Rome. He is the recipient of the 1991 IJCAI Publisher's Prize, prize Intelligenza Artificiale 1993, an ECCAI Fellow, and president of the RoboCup Federation (2011–2014). He heads the research laboratory Cognitive Robot Teams, which addresses cognitive robotics, cooperation in multirobot systems, human robot interaction, and several application domains, including service robots, disaster response robots, and soccer player robots for RoboCup competitions.

Itsuki Noda is a research team leader of the Service Design Assist Research Team of Center for Service Research, National Institute of Advanced Industrial Science and Technology (AIST), Japan. He received B.E., M.E., and Ph.D. degrees in electrical engineering from Kyoto University, Kyoto, Japan, in 1987, 1989, and 1995, respectively. He was a visiting researcher at Stanford University in 1999 and worked on the Council of Science and Technology Policy of Japanese government in 2003. He is interested in multiagent social simulation, machine learning, and disaster mitigation information systems, and is the current president of the RoboCup Federation.

A. Fernando Ribeiro is an associate professor at the University of Minho in Guimarães, Portugal. He created a robotics laboratory where many research and industrial projects are carried out; he also created a technological University of Minho spin-off company called SAR. His main research topics are mobile and autonomous robotics, image processing and computer vision general automation, and rapid prototyping. He won several scientific awards and is a trustee of the RoboCup Federation. He also promotes all kinds of robotics especially among young people through visits to schools, fostering robotics clubs, organizing events (three editions of the National Festival of Robotics), RoboParty (now in its seventh edition), and the organizing committee of RoboCup Junior.

Peter Stone is an Alfred P. Sloan Research Fellow, a Guggenheim Fellow, an AAAI Fellow, a Fulbright Scholar, and the University Distinguished Teaching Professor in the Department of Computer Science at the University of Texas at Austin. His research interests include machine learning, multiagent systems, robotics, and e-commerce. In 2003, he won a CAREER award from the National Science Foundation for his research on learning agents in dynamic, collaborative, and adversarial multiagent environments. In 2004, he was named an ONR Young Investigator for his research on machine learning on physical robots. In 2007, he was awarded the IJCAI 2007 Computers and Thought award. In 2013 he was awarded the University of Texas System Regents' Outstanding Teaching Award and in 2014 he was inducted into the University of Texas, Austin Academy of Distinguished Teachers.

Oskar von Stryk is a full professor of computer science at Technische Universität Darmstadt where he heads the Simulation, Systems Optimization, and Robotics Group. His research focuses on biomechanically inspired robots, cooperating teams of autonomous mobile robots, numerical simulation, optimization, and control of dynamical processes. His research results have been honored with the first prize of the EURON/EUROP European Robotics Technology Transfer Award, the Louis Vuitton Best Humanoid Award, and several RoboCup World Championships in autonomous humanoid and four-legged robot soccer teams.

Manuela M. Veloso is the Herbert A. Simon University Professor in the Computer Science Department at Carnegie Mellon University. She researches in AI and robotics, and directs the CORAL research laboratory for the study of multiagent systems where agents collaborate, observe, reason, act, and learn. Veloso is an IEEE Fellow, an AAAS Fellow, and an AAAI Fellow. She is the past president of AAAI and past president of RoboCup. She received the 2009 ACM/SIGART Autonomous Agents Research Award for her contributions to agents in uncertain and dynamic environments, including distributed robot localization and world modeling, strategy selection in multiagent systems in the presence of adversaries, and robot learning from demonstration.