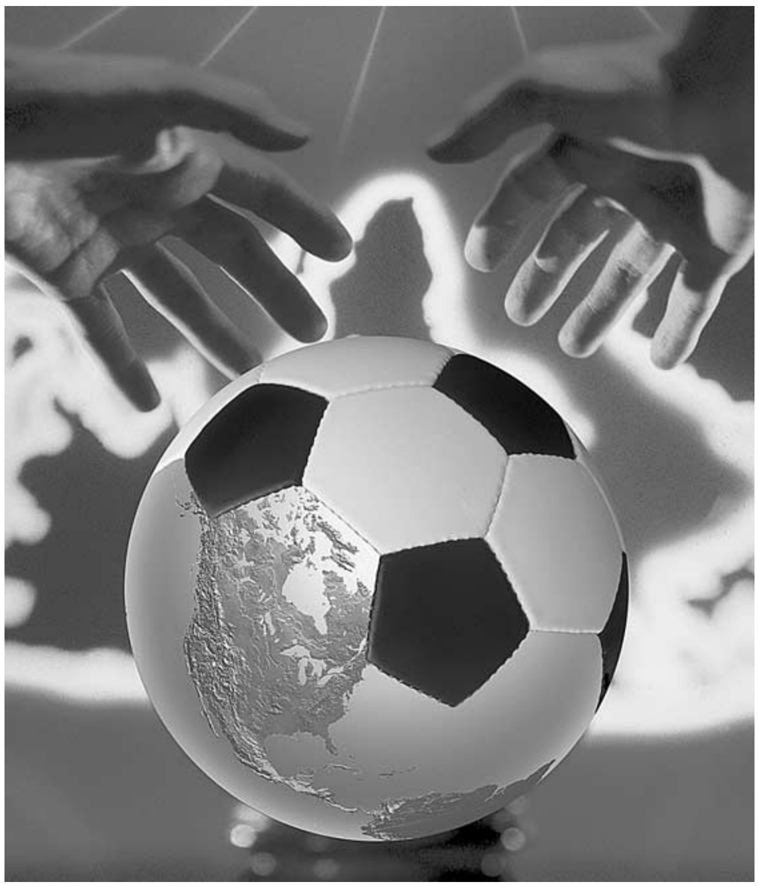
The Road to RoboCup 2050

Past Progress Brings Us Towards a Research Road Map for Further Competitions and Developments



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The ultimate goal of the RoboCup initiative is stated as follows [1]:

By mid-21st century, a team of fully autonomous humanoid robot soccer players shall win the soccer game, comply with the official rule of the FIFA, against the winner of the most recent World Cup.

We consider this goal from the perspective of how close we are to it and what has to be done to reach it.

The Year 2050 Goal

What does it mean to implement human-like behavior in robots, and how can we make them perform better than

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humans? We have asked representatives of different RoboCup robot leagues (humanoid, rescue, small size, middle size, and Sony legged) to outline their road maps for the future based on their experience in RoboCup. They have been asked to consider the year 2050 goal and measure their progress using the Fédération Internationale de Football Association (FIFA) laws. This was a difficult task, requiring the forecasting of technical developments over the next 50 years. Not surprisingly, answers have been very conservative. We received concrete dates from the leagues already at work, while the Humanoid league is still thinking about where to begin. The answers in this article represent an important first step in creating research road maps for RoboCup. This effort will provide the basis of future revisions and refinements of the RoboCup road map.

Asada and Kitano argue: "This goal may sound overly ambitious given the state of the art technology today. Nevertheless, we believe it is important that such a long range goal be claimed and pursued. It took only 50 years from the Wright Brothers' first aircraft for the Apollo mission to send men to the moon and safely return them to the earth. Also, only 50 years after the invention of the digital computer, Deep Blue beat the human world champion in chess. We recognize, however, that building a humanoid soccer player requires an equally long period and the extensive efforts of a broad range of researchers, and the goal will not be met in any near term. Obviously, in order to claim to be *real* robot soccer, it has to be done by a humanoid robot that can run fast, kick and dribble a ball, and jump to try a miracle heading shot. Humanoid players have to be biped robots, just like actual human players" [1].

A machine was able to beat the human chess champion, but it was not done using human-like intelligence (note that there are other games, like Go, that cannot be handled this way). For chess, it was only necessary to compute good moves, while soccer requires action in the real world. The question of *how* a machine might play a soccer game shows the differences. What are we willing to accept as soccer play, and what is needed to prevent the actors, especially the humans, from harmful effects?

Of course, human-like kicking skills and body performance are required, but do we allow the robots to use wireless communications of a broad bandwidth such that they can exchange pictures and plans? Are they allowed to have omnidirectional vision? We might allow them to calculate appropriate flight parameters for scoring and use the data for setting their kick devices. But how much power is allowed for the kicks? There is also a question of safety. The robots should have heights and weights comparable to the human ones (at least for safety reasons) and need to have two legs, but what else should make them look like soccer players? How do the robots have to act?

FIFA Laws

Some of these questions are answered by referencing the official rules of the FIFA, but not all. Will we, for example, allow the players to change batteries (or related systems) during the play?

Comparing the FIFA rules (especially the "Laws of the Game" [2]) with recent RoboCup rules [3], [4], we discover as main differences

- the playing field size, boundaries, and dimensions (FIFA laws 1, 9, 11, 15, and 17)
- the number of players (FIFA law 3)
- the players design, skills, power, and outside inference (FIFA laws 4, 7, and 12).

Since FIFA assumes human players, the differences actually concern even more aspects than depicted by the laws. From these differences, we can conclude that the progress of robot soccer can be measured as steps toward the use of ordinary playgrounds with no special boundaries, markers, or lighting conditions. It can also be measured by the number of players on the teams and, of course, by the design of the players.

Challenges

Robot soccer is considered a benchmark for the progress of robotics and artificial intelligence (AI). As one of the major applications of RoboCup technologies, the unmanned search-and-rescue (USAR) scenario is investigated. RoboCup initiated the RoboCup Rescue project to specifically promote research in socially significant issues.

Many technical and scientific problems have to be solved to meet these requirements. The following fields of research have been identified in [1]

- basic design, including surface and frame materials, power supply, actuation systems, and mechanical design
- basic control issues, including high performance mobility, behavioral robustness, behavioral complexity, and human control of high degree-of-freedom (DOF) systems
- sensory systems, including vision, auditory, and other sensing systems like force sensors of human skin, sensor fusion, sensory-motor-integration
- high-level cognitive systems, including strategy, learning, issues of brain and cognitive science, as well as the embodiment of intelligence in systems with high DOF.

Following recent trends, we could also ask for emotions!

Besides the necessary technical progress of the robots, it is also important to note that the conditions for the RoboCup competitions and rescue demonstrations will inevitably change. We will need larger fields, but the necessary improvements of perception (by better sensors and intelligent processing) must make it possible to use ordinary gymnasiums. It belongs to the challenges of RoboCup to use and develop cheap devices such that university teams can build their robot teams. Nevertheless, to have 11 humanoid soccer robots or a rescue robot team of reasonable size will exceed the budget of most universities. Therefore, we need to organize cooperation. A special challenge is the composition of teams of robots that are built by different institutions.

All these questions have to be answered by 2050 in a convincing way, and the appropriate materials and methods have to be developed. We now come to a closer look at the leagues.

Humanoid League

In this new league, the RoboCup Federation must reach its target of "by the year 2050 develop a team of fully autonomous humanoid robot that can win against the human world soccer champions" (H. Kitano, 1996).

The definition of "humanoid," besides the solutions to several technical issues, must be determined in order to successfully accomplish this goal.

Definition of Humanoid

We can distinguish three aspects of this problem: physical definition, capabilities, and behavior.

The physical aspects define the external aspects of the robot: head, body, legs, arms, weight, ratio between the height and the surface in contact with the ground, and the form of the ground surface. They give the geometrical parameters acceptable to qualify a robot as a player.

The capabilities define all the set of skills that can be integrated in the robot. What capabilities of communicating with other players should we allow; can we accept that the robot team is quickly able to exchange a lot of information with every player? Do we allow the robots a 360° range of vision? Can we accept that a humanoid robot can run forward and backward at the same speed?

The behavior defines all the rules that must be integrated in the robots. For instance, we must guarantee capabilities of "collision avoidance" for the safety of players. It can define a limit of speed for the robot (could we accept a player running 100 m in 5 s?). It requires a robot to play with all of its body so that humans can anticipate its future movements.

Scientific Challenges

Here we can distinguish four levels: materials, locomotion, sensor fusion, and team coordination.

There is a serious need for innovations in materials and devices for humanoid robots. First, "artificial muscle" is an essential material that enables robots to run and jump. Current actuator systems are too fragile to sustain jumping and running behaviors while walking, and other precise behaviors are also implemented. Such a device might have parallel and redundant mechanisms so that it can sustain its performance for degradations and damages. Second, materials that enable us to build robots with softer surfaces, as well as the strength to sustain its structure, are needed. Surface materials may be combined with tactile sensor systems so that contact with the environment can be sensed. The source of energy may need to be changed. New technologies, such as a fuel cells, enable large and sustainable electricity while producing only water as by-products of its reaction. Numbers of devices, from sensors to structural and surface materials, need to undergo a series of innovations and replace existing technologies.

Regarding locomotion, some important steps need to be taken, such as giving robots the ability to perform a simple walk (actually, it seems that humanoid robots are able to walk slowly). The second step is to enable humanoid robots to fall down and recover to standing. Then, the next step is the ability to walk quickly and run (with only one foot in contact with the ground at a time). From the scientific aspect, this means control of the dynamic model of the robot to compute anticipation to prepare the impact when the foot enters contact with the ground. Due to the complexity of such dynamic models, the problem of real-time programming is an important issue (learning may be an alternative solution). After the controlling of the running mode, control of the whole body while jumping must be studied. This control must integrate the problem of collision avoidance (while players are kicking with the head, for instance). Finally, real-time transition between all movements must be solved. This means finding intersection points between two trajectories.

Sensor fusion is a common problem at RoboCup. Here the problem is to close the loop between high-level sensors (vision) and low-level control. The manipulation expected from the robot is the ability to maintain the ball in the air without falling down (alone at first and with a number of players later). In this case, vision must allow the anticipation of the next position to kick the ball and locomotion must move the robot to this point. This real-time three dimensional (3-D) recognition must work outdoors in unconstrained lighting conditions. This first challenge must be followed by controlling the ball with the feet while running. The dribbling challenge must be performed quickly, maintaining the requirement of collision avoidance in front of dynamical obstacles.

The coordination challenge will be solved very late because it is very closely linked with the abilities of the robots and/or the rules. Here, the problem is to define in real-time the coordination of the team. We can imagine, if the models of the robots are perfect, the "God algorithm" that will define optimal organization. The question is: Can a full mathematical formulation of this problem be done? In fact, it seems impossible to answer this question seriously.

First Steps

As a first step towards fully autonomous humanoid robots, RoboCup is an exposition of teleoperated humanoid robots and virtual humanoid soccer games by teams of simulated humanoid robots with high-quality computer graphics, accurate physics simulation, and vision and sensor simulation [1]. Robots eligible to participate in the 2002 RoboCup Humanoid League shall meet the following requirements

- walk using two legs—no wheels are allowed to assist the walk
- include appropriate body proportions with heights in different categories of about 40/70/120/180 cm.

The competitions in 2002 will consist of two challenges

- race from one point to another and return
- penalty kick in front of an empty an goal

and a simple game

- penalty kick with an opposite goal keeper
- game one-one or two-two.

Rescue Robots

Robots can assist USAR workers in many ways. One important task is victim detection. We propose a victim-detection scenario emulating how rescue workers currently search, whereby one or more robots are deployed through an entry void into a confined space, search for and locate victims, allow rescue workers to assess the victim's condition by talking with them and even dropping off a radio or bio-monitor, then exit the rubble before losing battery power.

A road map of technologies needed for victim detection can be considered as an evolution of competencies in mobility, sensing, mapping, planning, power management, communications management, and human-robot interfaces. We see six levels of competence:

- *Robust teleoperation:* Robots that can handle rubble and confined spaces are teleoperated. The operator handles all the control, mapping, and planning using the topological wall-following strategies developed by fire rescue workers. Sensor suites should be able to detect the basic affordances of a survivor: heat, motion, sound, and color. In order to be robust, the robot must have on-board intelligence that allows it to re-establish lost communications. The operator is responsible for estimating the remaining mission time based on power consumption and distance to exit. The user interface is visual and capable of displaying data from multiple sensors simultaneously.
- *Intelligent assistance:* The next level is for the robot or workstation to actively aid the operator. The operator still directs and plans the robot's actions, but these are carried out under a guarded motion regime. The robot also cues the operator to signs of survivors, aids the operator in constructing and maintaining the topological map and location of victims, and estimates the time left in the mission before the robot must begin its egress from the site. The user interface should now support views from other robots (e.g., collaborative teleoperation).
- *Semi-autonomous control:* At this point, the robot is capable of autonomous execution of portions of the victim-detection script, as well as automatic pose control of polymorphic platforms. Sensing is still cooperative, but the robot ensures that the search covers the volume of interest and provides sensor fusion of cues. It also estimates the power availability for performing intensive tasks with margins for returning to the egress site. The interface displays adapt to the context and user preferences.
- *Victim assessment:* While navigation and victim detection have become fully automated, victim assessment is still cooperative. The robot can now carry and deploy radios or bio-sensors to leave behind. The user interface is now multimodal instead of relying only on visual displays.
- *Metric map making and planning:* At this level, basic control swaps from topological representations and maps to metric maps and optimal searches.
- *Structural assessment:* Building on the ability to make 3-D metric maps, the robot also is able to add data about the volumes that allow the operator to characterize the structure and make decisions for victim extraction.

Sony Four-Legged Robot League

The Sony four-legged robot league has different conditions than the other leagues. The main difference is that Sony has been developing the robot platform that all teams must use. It is difficult to anticipate how Sony will improve the robot platform. In this article, we discuss the robot hardware issue based on a general technology tendency, but the size of the robot may be almost the same as the current robot platform.

Two Basic Future Targets

Based on this assumption, we propose two clear targets for the four-legged robot league. The first one is "to win a human-controlled robot team game." We should be careful of the basic skills of the human-controlled team. The speed of walking and ball-handling skills of the human-controlled team must be comparable with an autonomous robot team. In addition, the interface for controlling the robots by a human must be good and fast enough to precisely control the robots. In order to develop such a human-controlled system, it is better to define a basic interface to a remote-control PC, so that the human-controlled team can use the developed basic skills through this interface. Then, this target will become a higher level task competition (such as decisions, collaborations, and strategy) and will accelerate development of these technologies.

The second milestone is "to win a human World Cup Championship with FIFA rules." It may be ambitious to define this target in the four-legged robot league because the size of the robot and its moving speed are not proper for the FIFA field and the ball. However, we would like to propose the same target as in the humanoid league. This target must be a good motivation to develop running/jumping four-legged robots [5].

One thing we have to consider is the use of wireless communications. Beginning in 2002, we will start to use a wireless LAN (WLAN) system so that the robots can communicate with each other. However, the final communication method among players must be by voice and gesture. Of course, in real life applications, wireless communication must be an important ability of the machines. Therefore, it is important for RoboCup to consider the development of the wireless communication system that should not be used in the final target but for real life applications.

Considering these facts, we think the main technical issues involve how to reduce the constraints of the playing environment.

Current Status

- *Field:* The field size is about 2 × 3 m. The ball and the goals are color painted. There are walls surrounding the field with a 45° slant. There are six color-painted poles (landmarks) for localization. The playing field is covered by a green napless carpet. The field is further surrounded by a light gray wall to avoid color confusion in the robot with the color of the spectators' clothes.
- *Players:* There are three robots on each team.
- *Illumination:* The illumination conditions on the field are well controlled. For example, in RoboCup-01, Seattle, the luminance on the field was from 800-1,000 lux, and the color temperature of the lighting was about 3,800 K. We kept this condition during the event.
- *Game Procedure:* The game starts by hitting the touch sensors in the back or on the head. If a goal is made, team members pick up the robots and put the robots on the particular place. The game length is 10 min each half. Because there are walls surrounding the field, there is no throw-in situation.

Year 2005

- *Field:* The size is about 3 × 4 m. No color-painted items. There are markers that can be distinguished by shape or texture. Some bumps with about 1-cm height for simulating a real ground condition. Low walls.
- *Players:* Five players for each team.
- *Illumination:* Rough control within the camera specification (400-1,500 lux).
- *Game procedure:* Automatic game start configuration by WLAN commands.

Year 2010

- *Field:* The size is about one-tenth of the FIFA field. No special markers. No walls.
- *Players:* Running and jumping four-legged robot at human running speed.
- *Illumination:* Indoor without any special lighting control.
- *Game procedure:* No human assistance but the wireless communication system.

Year 2030

- *Field:* The size is the FIFA field.
- *Players:* 11 for each team.
- *Illumination:* Outdoor.
- *Game procedure:* No human assistance or wireless communication system.

Year 2050

Safety and reliability must be taken into consideration.

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 limited vision. The robots are fully autonomous, i.e., all their sensors, actuators, power supply and (in most cases) computational power are onboard, and no external intervention by humans is allowed except to insert or remove robots into 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.

Past and Present Research Issues

In the earliest RoboCup MSL games, there was a natural focus on vision issues, namely on color segmentation algorithms. All the teams used video cameras, from simple Web cams to more sophisticated models. Achieving good color segmentation with fast algorithms was (and still is) a fundamental problem to be solved in the MSL; the whole team performance depends on this because relevant objects have distinct colors.

During the first games held in Nagoya, Japan, in 1997, no participating team included robots that could self-localize. Navigation was made based on the relative posture of relevant landmarks, e.g., moving around the ball until the opposite goal was seen behind it. The 1998 games, after a clear demonstration of superior behavior by the robots of the CS Freiburg team, showed that the ability to self-localize is a very important advantage for any team. Each of those robots were endowed with a self-localization algorithm based on the readings of the distances to the field walls by an on-board laser range finder (LRF) [6]. The correlation between LRF measurements and a geometric field model provides a very accurate estimate of each robot posture, as well as rough information on opponent robot positions, corresponding to situations where the walls can not be "seen" by the LRF because there is an opponent robot in between.

The performance of the CS Freiburg team motivated other teams to tackle the self-localization problem. A couple of teams also chose the LRF solution, due to its superior accuracy characteristics. Most teams, however, could not afford to buy an LRF per robot, so vision-based self-localization became a natural option as video cameras were available anyway. Iocchi and Nardi, from the Italian ART team, were the first to develop this strategy, in 1999, by using the soccer field lines (white painted on green) as natural features extracted, applying the Hough transform, from an image taken by a camera positioned at the robot front, together with a geometric field model and odometry information [7]. One year later, Marques and Lima introduced another Hough transform-based algorithm to determine the robot posture from a single image taken by an omnidirectional catadioptric system, composed of a video camera and a mirror built to preserve the bird's-eye view of the field [8]. Actually, omnidirectional vision, even though present from the very beginning in MSL robots, became a popular topic during the 2000 MSL games. Omnidirectional catadioptric vision systems were used to provide the soccer robots with a full view of the surrounding field, so that they could determine, from a single image, the ball position, their posture with respect to the goals, the teammate and opponent locations, etc. [9].

Another issue that proved to give important advantages to a team was the actual mechanical design. Teams such as the Iranian Sharif CE (MSL winner in 1999) and the Italian Golem (second place in 2000) benefitted from their (semi or fully) omnidirectional-based robot designs.

Future Research Issues

Even though most contributions achieved so far by RoboCup MSL researchers refer to "low-level" perception and navigation issues, it is clear that the major scientific challenge concerns the ability to discover solutions and methodologies to endow multirobot teams with cooperative behavior and improve teamwork. Nevertheless, it must be stressed that some of the achievements in perception and navigation are unique in RoboCup due to its integration within more complex architectures that include task planning, coordination and execution, as well as to its solution through fast algorithms—a strong requirement in a very dynamic and adversarial environment as the one experienced during a robot soccer game.

Nevertheless, some teams have already made serious efforts towards showing cooperative behaviors, such as passes between teammates, defending the goal temporarily left unoccupied by the goalkeeper or an undefended field zone, or supporting the player in possession of the ball during an attack [10]. What seems to be lacking are solutions to support the experimental results on formal methods of logical verification, performance evaluation, and behavior design from specifications.

An important step towards team coordination and cooperation is the development of distributed world model representations, where information about relevant objects is obtained from the measurements made by different sensors from different teammates. Guttman et al. describe a method based on Markov localization [11] for cooperative ball location that enables a robot that cannot see the ball to pursue it [12]. Nevertheless, more work needs to be done in this area, namely by fusing the information from sensors other than vision (e.g., LRF, sonars, infrared) and handling the uncertainty in the measurements due to sensor noise and incorrect estimates of the observing robot localization.

Another research topic of interest for some of the teams is the ability to learn individual and cooperative behaviors [13]. Reinforcement learning theory and other methods of (multi) robot task design through learning based on approximations to optimal solutions that could only be obtained otherwise through dynamic programming methods with the corresponding high computational power cost is a promising research topic for the future.

Current discussions on MSL rule modifications concern wall removal (with the goal of improving perception robustness by not isolating the robot perception systems from "external-world" noise, such as people or other objects with colors similar to the ball and goal colors), allowing the robots to include ball-manipulation devices (to improve ball control and avoid going out of the field should the walls be removed) and automatic refereeing (to make the robots respond automatically to referee decisions communicated through wireless networking, currently used by most of the teams).

As for a tentative future research road map in the MSL, we envision the following milestones:

- *2005:* ability to play at the current level without walls, including automatic refereeing.
- *2010:* ability to play under noncontrolled changing illumination conditions, with ball-manipulation devices and demonstration of teamwork.
- *2020-2040:* demonstrations of teamwork, including learning, and usage of ball-manipulation devices, in a larger field and with an increase on the number of players per team (up to 11).
- *2050:* reusability of teamwork, perception, navigation, ball manipulation, and learning MSL methods in an 11-player humanoid team.

Small-Size League

In the small-size RoboCup league (SSL), each team is composed of five robots that play against each other on a field the size of a ping-pong table. Recently, it was agreed to increase the field size to around 2.8 × 2.4-m starting in 2002, during the Japan tournament. The field is surrounded by low walls with a 45° slope that does not allow a kick to rebound the ball towards the field. The main difference with the MSL, apart from the size of the robots and the size of the field, is the global video camera used by each team to get a bird's-eye view of the game. The camera is located 3 m above the field, and the image is processed by an off-field computer that localizes the color markers of the robots (there is a yellow and a blue team) and the orange ball. Provided with this information, the off-field computer calculates the movements of the robots and the general strategy and sends signals to the robots using a wireless link. The signals can be as simple as the velocities of the wheels or can involve more complicated operations ("rotate 30° clockwise").

The four main technical issues associated with the SSL are the following:

- *Robust color processing and color tracking.* The lighting at tournament halls is very irregular; there are shadows and unpredictable variations during a game. The software has to surmount these difficulties while processing video frames provided by inexpensive cameras. In recent years, most good teams have solved these issues, and we do not see them losing the robots or the ball.
- *Robust mechanical design.* A robot able to play at a good level in the SSL must be fast (1-2 m/s maximal speed) and able to

resist strong collisions. Typically, SSL robots can fall from a table and continue playing. There has been a new emphasis in mechanical design during the last two years with the introduction of such innovations as omnidirectional drive (Cornell 2000) and dribbling bars that allow robots to control the ball and pass it (Cornell 2001).

- *Robust wireless communications.* This might be considered the single most important unsolved issue in the SSL. Most teams use the same RF chips and this has led to significant interference problems in the past. Tournaments have become too long because it is very difficult to schedule simultaneous games. A solution such as WaveLan cards or Bluetooth modules will be explored in the future.
- *Good programming of robot behavior.* It can be safely said that most teams in the SSL have adopted a pure reactive design with simple strategic goals. The fact that the field of play is too small relative to the size of the robots means that it does not pay to compute too complicated strategies. The horizon of most systems is just a few frames into the future, since the robots are so fast relative to the size of the field. Thus, enlarging the field has to become a major research issue if more sophisticated strategies are to be programmed.

Past and Present Results

The SSL has had three champions in five tournaments. The Carnegie Mellon Team (CMU) won the 1997 and 1998 tournaments. Their major achievement was to put together a coherent system for the first time. Their vision system was also made available to other teams that have used it to bootstrap their own teams. CMU used a minimalist approach to onboard electronics, putting most of the intelligence of the system in the off-field computer, an approach that has been followed by many other teams.

The 1999 and 2000 tournaments were won by the Cornell team. Their major contribution in 1999 was showing sophisticated path planning with fast robots that used several behaviors that have become standard. The 2000 team was even more innovative because it used an omnidirectional system with three wheels that gives better control over the robots. They introduced the dribbler, a rotating bar that makes the ball rotate against the robot in such a way that the robot has full control of the ball. In 1999, hard-shooting mechanisms were also introduced for the first time; the FU-Fighters team could shoot the ball at speeds that defied the human eye. Therefore, the horizontal walls around the field were removed, in 2000, to discourage uncontrolled ball shooting. Most good teams, however, have introduced stronger shooting devices from year to year.

The winner of the 2001 tournament, Lucky Star from Singapore, showed how excellent control of the system and precision in the robot's movement can lead to victory, even against teams with more sophisticated mechanics. In the same year, the first really good local-vision team played in the tournament. The FU-Fighters Omnivision, a team with small local cameras, won against all other local-vision teams and showed that the algorithms from the MSL could be ported to the SSL. The FU-Fighters introduced an inexpensive parabolic concave mirror system with which the self-localization of the robots can be computed. Using the video frames sent by a wireless transmitter to an off-field computer, it is possible to find the position of the ball, the other robots, and the goal mouths. The FU-Fighters Omnivision showed a system which can be compared to the best systems in the current MSL.

Future Research Issues

It is very difficult to provide a road map for the development of robotic soccer in the SSL, which encompasses more than a few years. The advances in this field are coming so fast that we do not see the need for separate middle-size and small-size leagues beyond the year 2010. The miniaturization of computer components will allow us to put the equivalent of four current workstations in a small-size robot at that time and allow us to do all the processing on-board without the need of a global camera. Therefore, the SSL and the MSL will necessarily converge—even before 2010. The development of walking robots up to that year will move the interest from games between robots with wheels to games between humanoid robots. Research funds and research groups will start moving in that direction before the end of the decade.

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

- *2002:* larger field (2.8 × 2.4-m), global camera.
- *2003:* no human intervention (for moving robots) is allowed (full-automatic game with human refereeing).
- *2004:* robots with a local-vision camera become competitive in the 2.8 × 2.4-m field.
- *2005:* larger field, (6 × 5-m), seven versus seven robots, global vision.
- *2007:* a local-vision team is competitive with the top global-vision teams.
- *2008:* 11 vs 11 robots, global vision.
- *2010:* larger field of 9 × 6-m, 11 global-vision robots, the SSL and the MSL fuse.

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Keywords

Autonomous robots, RoboCup, humanoid robots.

References

[1] H. Kitano and M. Asada, "The RoboCup humanoid challenge as the millennium challenge for advanced robotics," *Adv. Robot.*, vol. 13, no. 8, pp. 723-737, 2000.

[2] International Football Association Board. Laws of the game. [Online]. Available: http://www.fifa.com/refs/laws_E.html
[3] Home page of RoboCup Middle Size Robot League. [Online]. Available: http://smart.informatik.uni-ulm.de/ROBOCUP/f2000/
[4] Laws of the F180 League 2002—Draft 0.2. [Online]. Available: http://www.itee.uq.edu.au/~wyeth/f180rules.htm.
[5] T. Yamamoto, M. Fujita, M. de Lasa, S. Talebi, D. Jewell, R. Playter, and M. Raibert, "Development of dynamic locomotion for the entertainment robot (Teaching a new dog old tricks)," in *Proc. CLEAWER 2001*.
[6] J.-S. Gutmann, W. Hatzack, I. Herrmann, B. Nebel, F. Rittinger, A. Topor, T. Weigel, "The CS Freiburg team—Playing robotic soccer based on an explicit world model," *AI Mag.*, vol. 21, no. 1, pp. 37-46, Spring 2000.
[7] L. Iocchi and D. Nardi, "Self-localization in the RoboCup environment," in *Robocup—99: Robo Soccer World Cup III*, M. Veloso, E. Pagello, and H. Kitano, eds. Berlin Germany: Springer-Verlag, 2000.
[8] C. Marques and P. Lima, "A localization method for a soccer robot using a vision-based omni-directional sensor," in *Robocup 2000: Robot Soccer World Cup IV*, P. Stone, T. Balch, G.K. Kraetzschmar, eds.. Berlin: Germany: Springer-Verlag, 2001.
[9] P. Lima, A. Bonarini, C. Machado, F. Marchese, C. Marques, F. Ribeiro, and D. Sorrenti, "Omni-directional catadioptric vision for soccer robots," *J. Robot. Autonomous Syst.*, volume 36, no. 2-3, pp. 87-102, Aug. 2001.
[10] C. Candea, H. Hu, L. Iocchi, D. Nardi, and M. Piaggio, "Coordination in multi-agent RoboCup teams," *J. Robot. Autonomous Syst.*, volume 36, no. 2-3, pp. 67-86, Aug. 2001.
[11] D. Fox, W. Burgard, and S. Thrun, "Markov localization for mobile robots in dynamic environments," *J. AI Res.*, vol. 11, pp. 391-427, 1999.
[12] M. Dietl, J.-S. Gutmann, and B. Nebel, "CS Freiburg: Global view by cooperative sensing," in *RoboCup 2001: Robot Soccer World Cup V*, A. Birk, S. Coradeschi, and S. Takodoro, eds. Berlin, Germany: Springer-Verlag, to be published.
[13] Y. Takahashi, T. Tamura, and M. Asada, "Strategy learning for a team in adversary environments," in *RoboCup 2001: Robot Soccer World Cup V*, A. Birk, S. Coradeschi, and S. Takodoro, eds. Berlin: Germany: Springer-Verlag, to be published.

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