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RoboCup-2001

The Fifth Robotic Soccer World Championships

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■ RoboCup-2001 was the Fifth International RoboCup Competition and Conference. It was held for the first time in the United States, following RoboCup-2000 in Melbourne, Australia; RoboCup-99 in Stockholm; RoboCup-98 in Paris; and RoboCup-97 in Osaka. This article discusses in detail each one of the events at RoboCup-2001, focusing on the competition leagues.

RoboCup-2001 was the Fifth International RoboCup Competition and Conference (figure 1). It was held for the first time in the United States, following RoboCup-2000 in Melbourne, Australia; RoboCup-99 in Stockholm; RoboCup-98 in Paris; and RoboCup-97 in Osaka. RoboCup is a research-oriented initiative that pioneered the field of multirobot research of robot teams starting in 1996. In those days, most of the robotics research was focused on single-robot issues. RoboCup opened a new horizon for multirobot research: Teams of robots need to face 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.

RoboCup has truly been a research-oriented endeavor. Every year, the 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 toward this goal.

This article discusses in detail each one of the events at RoboCup-2001, focusing on the competition leagues. As an overview of the complete RoboCup-2001 (table 1 lists all the teams), and as an introduction to this article, we first provide a short description of the RoboCup-2001 events. The general chair of RoboCup-2001 was Manuela Veloso. The associate chairs in charge of robotic and simulation events, respectively, were Tucker Balch and Peter Stone.

International symposium: This was a two-day international symposium with presentations of technical papers addressing 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 are edited by program chairs Andreas Birk, Silvia Coradeschi, and Satoshi Tadokoro.

Figure 1. The RoboCup-2001 Participating People and Robots.

Two simulation leagues: These are the soccer simulator and the simulation rescue. The soccer simulator competition consisted of 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 RoboCup Simulation Rescue competition, with teams of fully distributed software agents, provided a disaster scenario in which teams with different capabilities, for example, firefighters, police crews, and medical teams, needed to conduct search and rescue for victims of a disaster. This event was held for the first time at RoboCup-2001.

RoboCup junior outreach: The RoboCup junior event hosts children 8 to 18 years of age interested in robotic soccer. The competitions and demonstrations include two on two soccer and robot dancing.

Four robot leagues: These leagues are the small-size robot, the middle-size robot, the Sony legged robot, and the robot rescue. The small-size robot competition consisted of teams of as many as five robotic agents of restricted dimensions, approximately 15 centimeters.[3] Off-board vision and computer remote control were allowed. The middle-size robot competition consisted of teams of as many as four robotic agents of restricted dimensions and a surface of approximately 50 centimeters[2] in which robots needed to have full on-board autonomy (table 4). The Sony legged-robot league consisted of teams of three fully autonomous Sony robots. Sixteen teams participated with Sony four-legged robots. The robot rescue competition was jointly held 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 three-story disaster scenario provided by the National Institute of Standards and Technology (NIST), where robots navigate through debris to search for victims.

Humanoid robot demonstration: RoboCup-2001, jointly with AAAI, held a demonstration of a humanoid robot. We are planning the first humanoid game for RoboCup-2002. RoboCup-2001 proved to be a truly significant contribution to the fields of AI and robotics and the subareas of multiagent and multirobot systems.

Robotics Leagues

Robots competed in four leagues at RoboCup-2001: (1) the small-size league, (2) the middle-size league, (3) the Sony legged-robot league, and (4) robot rescue. The small-size league, chaired by Raul Rojas, involves teams of five robots that play on a field about the size of a table tennis court with an orange golf ball. The

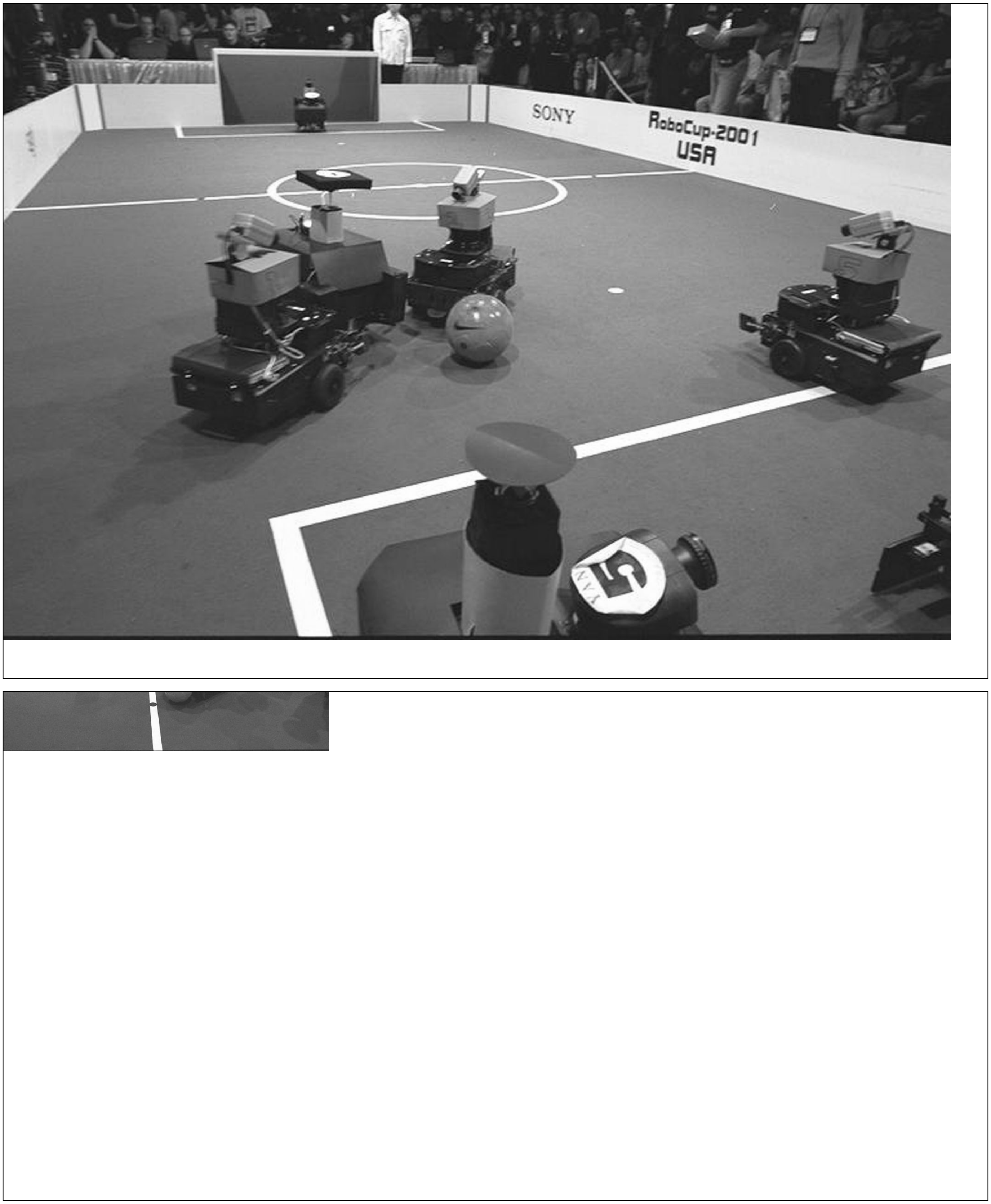


Figure 2. Two Views of the RoboCup-2001 Middle-Size League.

robots are limited in size to at most 18 centimeters in diameter. One of the key distinctions between the small-size league and the other leagues is that teams in the small-size league are allowed to place cameras over the field to determine the locations of robotic players and the ball. In most cases, teams feed the output of the overhead camera into a central computer that determines movement commands that are transmitted over wireless links to the robots. However, many researchers are interested in the challenge of developing small-size robots with onboard sensing only; the number of teams in this category has been growing each year.

The small-size field has evolved substantially in the last few years. Originally, the field was defined as a ping-pong table surrounded by 10-centimeter-tall vertical walls. However, it was felt that more "finesse" would be achieved in ball handling if the walls were angled; so, in 2000 the walls were set at a 45-degree angle and shortened to 5 centimeters, where the ball is likely to roll out of bounds if it is not handled carefully. Another evolution toward more realistic play was the addition of "artificial turf" on the field (actually a short green carpet).

The year 2001 marked the first time that more teams wanted to attend than could be accommodated at the competition. Space and time limited the organizers to approximately 20 teams in each league. Teams were required to submit technical descriptions and videotapes of their teams to qualify. In the case of the small-size league, 22 teams were invited, and 20 eventually made the trip to Seattle.

The competition was conducted as follows: Teams were divided into four groups of five teams each. The composition of the groups depended on a number of factors, including past performance and country-continent of origin. Within each group, a full round-robin competition was held (each team played every other team in the group). At the end of the round-robin phase, the top two teams in each group were allowed to proceed to the playoffs. The small-size teams that reached the playoffs were FU-FIGHTERS, LUCKY STAR II, KU-BOXES, ROGI TEAM, CORNELL BIG RED, 5DPO, ROBOROOS, and the FIELD RANGERS. Quarter finals, semifinals, and finals were held in a single elimination tournament, with an additional match to determine third place. The top finishers were (1) LUCKY STAR II, (2) FIELD RANGERS, and (3) CORNELL BIG RED.

Middle-size–league teams play on carpeted fields 5 meters wide by 9 meters long (figure 2). The robots are limited to 50 centimeters in diameter. Unlike the small-size league, no external sensing is allowed, and all sensors must be on board the robots themselves. Teams are composed of as many as four robots. An orange FIFA (International Soccer Association) size-5 ball is used.

Eighteen teams participated in the middle-size league at RoboCup-2001, which was chaired by Pedro Lima. Three groups of six teams each competed in round-robin matches, with the best eight teams proceeding to playoff games. The top three finishers in the middle-size league were (1) CS FREIBURG, (2) TRACKIES, and (3) EIGEN.

The Sony legged robots compete on a 3-meter by 5-meter carpeted field. Six colored landmarks are placed around the field to help the robots determine their location. A small plastic orange ball is used for scoring. Like the middle-size league, the Sony legged robots are limited to on-board sensing (including a color camera). All teams must use identical robots provided by Sony. In 2001, teams were composed of three robots each; in 2002, the teams will include four robots. The Sony legged-robot soccer league has been expanding each year to include new teams. RoboCup-2001 included 16 teams from around the world.

The Sony legged league was chaired by Masahiro Fujita. As in the other robot leagues, the competition was conducted in round-robin and playoff stages. For the round robin, teams were organized into four groups of four teams. Eight teams progressed to the playoffs. The top three finishers in the Sony legged-robot league were (1) UNSW UNITED'01, (2) CM-PACK'01, and (3) UPENNALIZERS'01.

The year 2001 marked the first year RoboCup included a robot rescue event (figure 3). The event was jointly organized by RoboCup and AAAI and chaired by Holly Yanco. In this competition, robots explored a simulated postearthquake environment for trapped or injured human victims. Seven teams participated in this event. No team did well enough to place, but two technical awards were given. Swarthmore College was given the Technical Award for Artificial Intelligence for Rescue, and Sharif University received the Technical Award for Advanced Mobility for Rescue. We expect this league to grow substantially in the next few years. The robot rescue competition is described in more detail in the companion articles in this issue.

Simulation Leagues

RoboCup-2001 featured the fifth RoboCup soccer simulation competition and introduced the first RoboCup rescue simulation competition. Both simulation platforms aim to capture

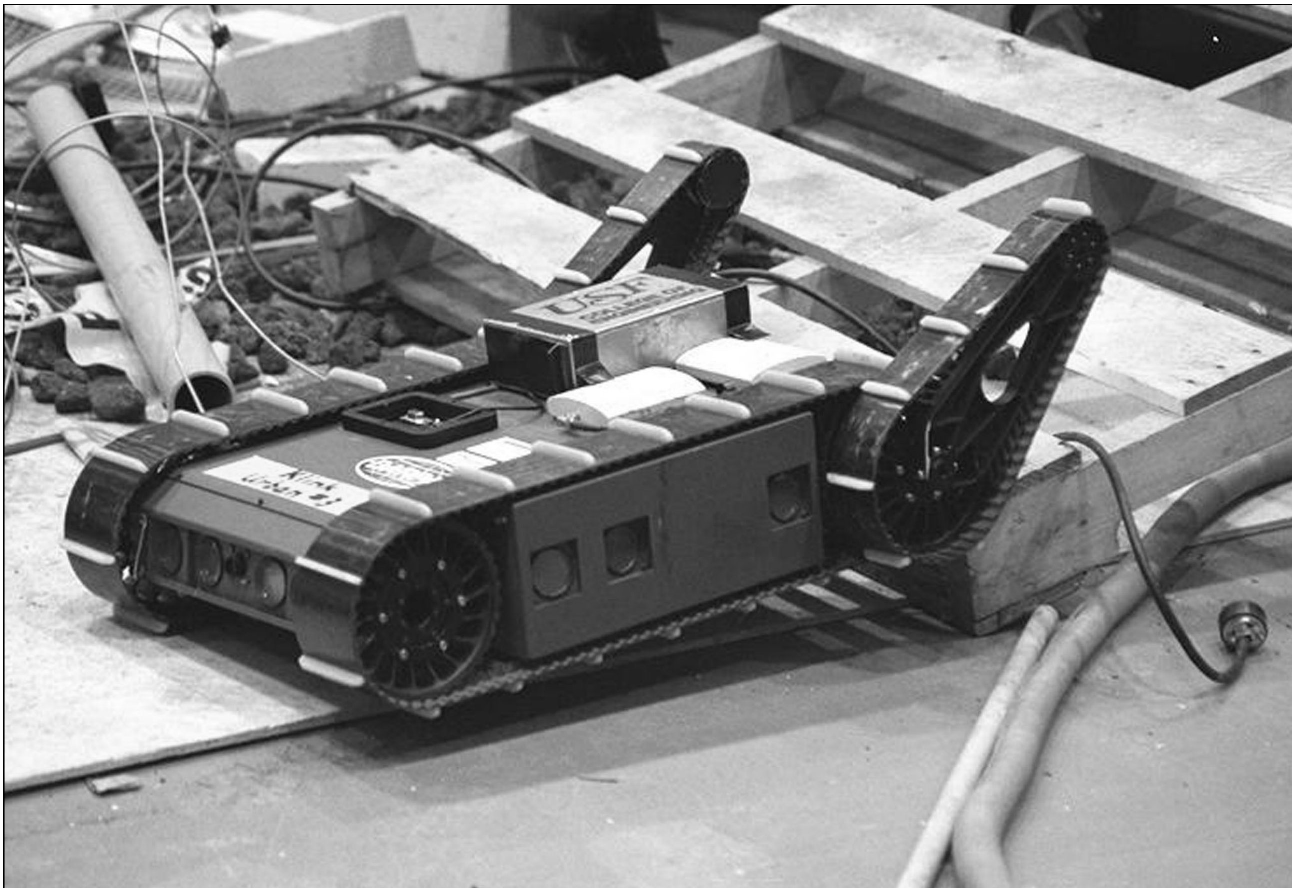


Figure 3. The RoboCup Rescue Robot League.

many of the challenges of the robotic leagues, without requiring participants to build physical robots. Like in the real world, simulator agents must deal with large amounts of uncertainty and both perceptual and actuator noise. Although the challenges of computer vision and mechanical design are abstracted away, simulator teams consist of greater numbers of agents than do their robotic counterparts and, thus, must address more large-scale multiagent issues. The ability to execute many more test runs in simulation than is possible with real robots also enables a larger range of possible approaches to agent control, including learning-based methods.

Soccer Simulation

The soccer simulator competition, chaired this year by Gal Kaminka, continues to be the most popular RoboCup event from the perspective of the number of entrants (figure 4). More than 50 teams met the qualification requirements, 42 of which actually entered the competition. The RoboCup soccer simulator (Noda et al. 1998) is an evolving research platform that has been used as the basis for successful international competitions and research challenges (Kitano et al. 1997). It is a fully distributed, multiagent domain with both teammates and adversaries. There is hidden state, meaning that each agent has only a partial world view at any given moment. The agents also have noisy sensors and actuators, meaning that they do not perceive the world exactly as it is, nor can they affect the world exactly as intended. In addition, the perception and action cycles are asynchronous, prohibiting the traditional AI paradigm of using perceptual input to trigger actions. Communication opportunities are limited, and the agents must make their decisions in real time. These domain characteristics combine to make simulated robotic soccer a realistic and challenging domain. Each year, small changes are made to the simulator both to introduce new research challenges and to "level the playing field" for new teams. This year, the biggest changes were the introduction of het-

RoboCup-2001 Scientific Challenge Award

Energy-Efficient Walking for a Low-Cost Humanoid Robot, PINO

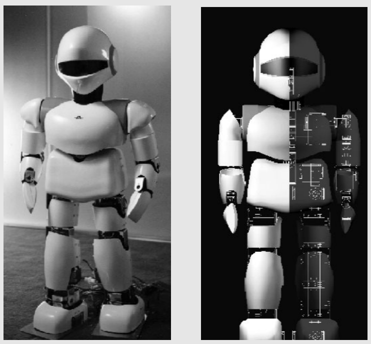


Figure A. PINO.
Left: Whole view. Right: Mechanism.

The RoboCup humanoid league, which is scheduled to start in 2002, is one of the most attractive research targets. We believe that the success of the humanoid league is critical for the future of RoboCup and will have major implications in robotics research and industry. Building humanoid robots that compete at RoboCup requires sophistication in various aspects, including mechanical design, control, and high-level cognition.

PINO is a low-cost humanoid platform composed of low-torque servomotors and low-precision mechanical structures. It has been developed as a humanoid platform that can widely be used by many RoboCup researchers in the world. Figure A shows the whole view and the mechanical architecture of PINO.

It is intentionally designed to have low-torque motors and low-precision mechanical structures because such motors and mechanical structures significantly reduce production cost. Although many humanoid robots use high-performance motor systems to attain stable walking, such motor systems tend to be expensive. Motors that are affordable for many researchers have only limited torque and accuracy. Development of a method that allows biped walking using low-cost components would have a major impact on the research community as well as industry. In the past, many researchers have studied a simple planar walker without any control torque (McGeer 1990). In such methods, walking motions are decided by the relationship between a gravity potential effect and structural parameters of the robots. Thus, there is no control over walking behaviors such as speed and dynamic change in step size.

In the biped walking method, we started with the hypothesis that the walker can change the walking speed without changing the step length if the moment of inertia of the swing leg at the hip joint has adequately been changed. We designed a control method using the moment of inertia of the swing leg at the hip joint. The method was applied to the torso of the PINO model in computational simulations and confirmed that the method enables stable walking with limited torque.

A cycle of biped walking can be subdivided into several phases: (1) two-leg supporting, (2) one-leg supporting, and (3) landing. Both legs are grounded in the two-leg supporting phase and landing phase, whereas only one leg is grounded in the one-leg supporting phase. In conventional biped walking algorithms, knees are always bent so that motors are continuously highly loaded. This approach is very different from normal human walking postures. It should be noted that most of the current control methods for humanoid walking are designed independently of the structural properties of the robot hardware. In general, these control methods require extremely large torque to realize desired walking patterns. Although knees are bent when walking on uneven terrain or major weights are loaded, the legs are stretched straight when walking on a flat floor. This posture can easily be modeled by inverted pendulum, which is known to be energy efficient. In addition, movement of the torso affects the overall moment of inertia and, thus, affects energy efficiency. Our goal is to mimic human walking posture to minimize energy through a combination of an inverted pendulum controlled by a swing leg and feedback control of torso movement.

The basic idea behind the low-energy walking method is to consider legs of humanoid robots, during the one-leg supporting phase, as a combination of an inverted pendulum model and a two–degree-of-freedom (DOF) pendulum model, assuming the structure of PINO to be a planar walker. In this case, the inverted pendulum represents the supporting leg, and the two DOF pendulum represents the swing leg. The inverted pendulum model is the most energy-efficient model of the supporting leg.

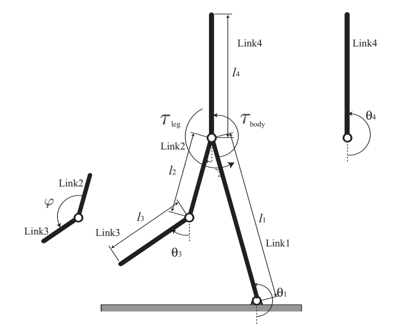


Figure B. Planar Four-Link Model of the Robot.

Figure B shows the four-link model with torso. This model consists of link1, link2, link3, and link4; link1 has a joint with the ground. We define every joint angle $\theta_1, \theta_2, \theta_3, \theta_4$ as an absolute angle of link1, link2, link3, and link4, respectively. We assume that every joint has a viscosity coefficient of 0.01 [N · m · s/ rad] and that the knee joint also has a knee stopper. Each link has uniformly distributed mass m_1, m_2, m_3, and m_4, respectively. Table A shows the link parameters of the four-link model that are obtained from the real PINO.

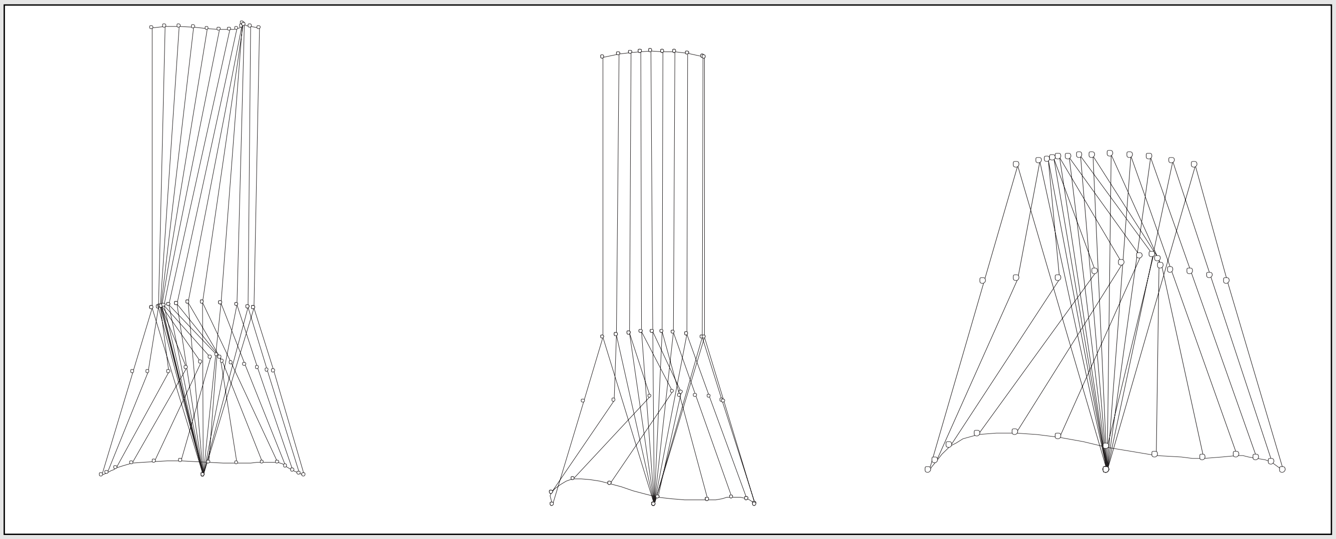
m_1	[kg]	0.718	l_1	[m]	0.2785
m_2	[kg]	0.274	l_2	[m]	0.1060
m_3	[kg]	0.444	l_3	[m]	0.1725
m_4	[kg]	3.100	l_4	[m]	0.4515

Table A. Link Parameters.

Given the control method to verify these hypotheses (Yamasaki et al. 2001), parameter spaces were searched to identify an optimal parameter set. Optimal solutions were found for three cases: (1) torso movement is controlled by feedback from body and leg movement, (2) torso is fixed vertically, and (3) the three-link model without torso is compared with the four-link model with torso.

erogeneous players and the introduction of a standardized coach language.

Heterogeneous Players Heterogeneous players were introduced to the RoboCup simulator for the first time this year in version 7.0 of the simulator.[1] In previous versions, teams could consist of players with different behaviors, but their physical parameters, such as size,



Left: Figure C. Result of the Foot Gait of Case 1. Middle: Figure D. Result of the Foot Gait of Case 2. Right: Figure E. Result of the Foot Gait of Case 3.

Figures C, D, and E show the foot trajectory for each case. Table B shows the initial angular velocity $\dot{\theta}_1$, $\dot{\theta}_2$, $\dot{\theta}_3$, $\dot{\theta}_4$ time to touch down t_2 and energy consumption. From table B, t_2 of the four-link model with torso is longer than that of the three-link model without torso t_2, and energy consumption of case 1 is smaller than that of case 2, although every angular speed is larger. From these results, we can verify that the walking motion with appropriate swings of the torso enables the robot to walk with lower energy consumption.

Value		**Case 1**	**Case 2**	**Case 3**
$\dot{\theta}_1$	[rad/sec]	1.736	0.962	3.374
$\dot{\theta}_2$	[rad/sec]	1.692	0.223	1.384
$\dot{\theta}_3$	[rad/sec]	0.000	0.000	0.000
$\dot{\theta}_4$	[rad/sec]	1.309	—	—
t_2	[sec]	0.319	0.406	0.296
Energy consumption	[J]	0.064	0.109	0.025

Table B. Results of Three Cases.

We chose the moment of inertia of the swing leg at the hip joint, and we applied feedback torque $\tau_{leg} = -k_{leg}\varphi$ to the hip joint. As a result, in the lower-limb model of PINO, the maximum torque required was reduced to the range of approximately 0.2 [$N \cdot m$] (at $k = 0.13$) to 0.35 [$N \cdot m$] (at $k = 0.22$). This enables the low-cost humanoid PINO to perform reasonably stable biped walking.

Further, in the four-link model with torso, it was verified that appropriate swings of the torso enable the robot to walk with lower energy consumption, as low as 0.064 [J].

In this study, we observed the interesting relationship between the control parameters and the walking behaviors, but understanding the details of the mechanism that realize such behaviors is our future work. This study demonstrates that the energy efficiency of humanoid walking can be altered when whole body motion is appropriately used. This is an important insight toward achieving practical humanoid robots for low-cost production as well as high-end humanoid seeking for ultra–high performance using whole-body movement.

OPENPINO

All technical information on PINO is now available under GNU General Public License and GNU Free Document License as OPENPINO (exterior design and trademarks are not subjects of GNU license). It is intended to be an entry-level research platform for possible collective efforts to further develop humanoid robots for additional research. Authors expect the LINUX-like community is building around OPENPINO.

Acknowledgments

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speed, and stamina, were all identical. This year, teams could choose from among players with different physical characteristics. In particular, in any given game, each team was able to select from identical pools of players, including the default player type from years past and six randomly generated players. At start-up, teams were configured with all default players. However, the autonomous online coach could substitute in the randomly generated players for any player other than the goalie. The only restriction is that each random player type

Figure 4. The RoboCup-2001 Simulation Leagues.

could be assigned to, at most, three teammates.

The random players are generated by the simulator at start-up time by adjusting five parameters, each representing a trade-off in player abilities: (1) maximum speed versus stamina recovery, (2) speed verus turning ability, (3) acceleration versus size, (4) leg length versus kick accuracy, and (5) stamina versus maximum acceleration. These parameterizations were chosen with the goal of creating interesting research issues regarding heterogeneous teams without creating a large disadvantage for teams that chose to use only default players. At the outset, it was not known whether using heterogeneous players would be advantageous. Experimentation leading to the competition established that using heterogeneous players could provide an advantage of at least 1.4 goals a game over using only the default players (Stone 2002).

Indeed, at least one of the top-performing teams in the competition (UvA Trilearn from the University of Amsterdam—fourth place) took good advantage of the heterogeneous players, with some observers commenting on their speedy players that they positioned on the sides of the field.

Standardized Coach Language Past RoboCup simulator competitions have allowed teams to use an omniscient autonomous coach agent. This coach is able to see the entire field and communicate with players only when the play is stopped (for example, after a goal or for a free kick). Typically, each team developed its own communication protocol between the players and the coach.

This year, a standardized coach language was introduced with the goal of allowing a coach from one team to interact with the players from another. The standardized language has a specific syntax and intended semantics. Teams had an incentive to use this language because messages encoded in the standardized language could be communicated even when the ball was in play (although with some delay and frequency limit to prevent coaches from "micromanaging" their players).

One offshoot of introducing a standardized

Figure 5. A RoboCup Junior Game.

language was that an auxiliary competition could be introduced: a coach competition. In this competition, entrants provided only a coach that was paired with a previously unknown team that is able to understand the standardized coach language. Entrants were judged based on how well this unknown team could perform against a common opponent when coached by the entrant's coach program.

Results For the second year in a row, a first-time entrant won the RoboCup simulator competition: tsinghuaeolus from Tsinghua University in China. They beat the brainstormers from Karlsruhe University in Germany by a score of 1–0, scoring the lone goal of the game during the third overtime period. The winners of the inaugural coach competition were the ChaMeleons from Carnegie Mellon University and Sharif-Arvand from Sharif University of Technology in Iran.

Rescue Simulation

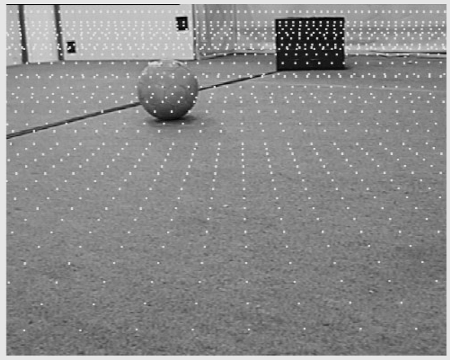
RoboCup-2001 hosted the inaugural RoboCup rescue simulation competition, which was chaired by Satoshi Tadokoro. The basis of RoboCup rescue is a disaster rescue scenario in which different types of rescue agents—firefighters, police workers, and ambulance workers—attempt to minimize the damage done to civilians and buildings after an earthquake. The setting was a portion of Kobe, Japan, the site of a recent devastating earthquake.

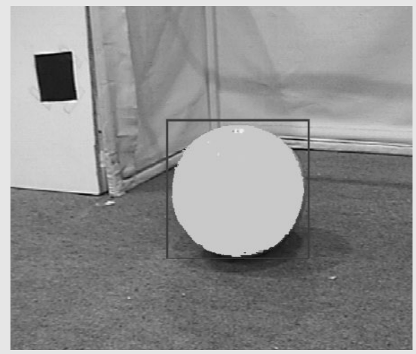
The simulator included models that cause buildings to collapse, streets to be blocked, fires to spread, and traffic conditions to be affected based on seismic intensity maps. Each participant had to create rescue agents for each of the three types as well as one control center for each type of agent (that is, a fire station, a police station, and a rescue center). The agents sense the world imperfectly and must react to dynamically changing conditions by moving around the world, rescuing agents, and putting out fires according to their unique capabilities. Communication among agents of different types is restricted to going through the control centers.

RoboCup-2001 Engineering Challenge Award

Fast Object Detection in Middle-Size RoboCup

Fast and reliable analysis of image data is one of the key points in soccer robot performance. To make a soccer robot act fast enough in a dynamically changing environment, we will reduce the number of sensors as much as possible and design fast software for object detection and reliable decision making. Therefore, in RoboCup, we think it is worth getting fast and almost correct results rather than slow and exact. To achieve this goal, we propose three ideas: (1) a new color model, (2) object detection by checking image color on a set of jump points in the perspective view of the robot front camera, and (3) a fast method for detecting edge points on straight lines. The other details of our robot (that is, its mechanical design, hardware control, and software) is given in Jamzad et al. (2000).





Left: Figure A. Position of Jump Points in a Perspective View of the Robot.

Right: Figure B. An Illustration of Ball Segmentation by a Surrounding Rectangle.

A New Color Model

We propose a new color model named HSY (the H is from CIELab, S from HSI, and Y from Y IQ color models [Sangwine and Horne 1998]). The reason for this selection is that the component Y in Y IQ converts a color image into a monochrome one. Therefore, comparing with I in HSI, which is the average of R, G, and B, Y gives a better mean for measuring the pixel intensity. The component S in HSI is a good measure for color saturation. Finally, the parameter H in CIELab is defined as follows:

$$H = \tan^{-1} b^*/a^*$$

where a^* denotes relative redness-greenness, and b^* shows yellowness-blueness (Sangwine and Horne 1998). H is a good measure for detecting regions matching a given color (Gong and Sakauchi 1995), which is exactly the case in RoboCup where we have large regions with a single color.

Object Detection in Perspective View

In the real world, we see everything in perspective: Objects far away from us are seen small, and those closer up are seen larger. This view is true for cameras as well. Figure 1 shows an image of the RoboCup middle-size soccer field with certain points on it. The points that are displayed in perspective to the robot's front camera are called *jump points*. They have equal spacing on each perspective horizontal line. Their vertical spacing is related to the RoboCup soccer field size. The actual spacing between jump points is set in such a way that at least five jump points are located on a bounding box surrounding the ball (which is the smallest object on the soccer field), no matter how far or how close the ball is. By checking the image color only at these jump points, there is a high probability that we could find the ball. In our system, we obtained satisfactory results with 1200 jump points.

To search for the ball, we scan the jump points from the lower right point toward the upper left corner. At each jump point, the HSY equivalent of the RGB values is obtained from a lookup table. Because we have defined a range of HSY for each of the standard colors in RoboCup, we can easily assign a color code to this HSY value. If a jump point is red, then it is located on the ball. Because this jump point can be any point on the ball, from this jump point, we can move toward right, left, up, and down, checking each pixel for its color. As long as the color of the pixel being checked is red, we are within the ball area. This search stops in each direction when we reach a border point that is a nonred pixel. In one scan of all jump points in a frame, in addition to a red ball, we can find all other objects, such as robots, the yellow goal, and the blue goal. For each object, we return its descriptive data, such as color, size, and the coordinate of its lower-left and upper-right corner of its surrounding rectangle and a point Q on the middle of its lower side (figure 2). Point Q is used to find the distance and angle of the robot from this object.

Straight-Line Detection

During the match, there are many cases when the robot needs to find its distance from walls. In addition, the goal keeper at all times needs to know its distance from walls and also from white straight lines in front of the goal. Because the traditional edge-detection methods (Gonzalez and Woods 1993) are very time consuming in real-time situation, we propose a very simple and fast method to find the edge points on straight lines as follows:

As seen in figure 3, to locate points on the border of the wall and the field, we select a few points on top of the image (these points are on the wall) and assume a drop of water is released at each point. If no object is on its way, the water will drop on the field, right on the border with the wall. To implement this idea, from a start point w_i we move downward until reaching a green point f_i. All candidate border edge points are passed to Haugh transform (Gonzalez and Woods 1993) to find the straight-line equation that best fits these points.

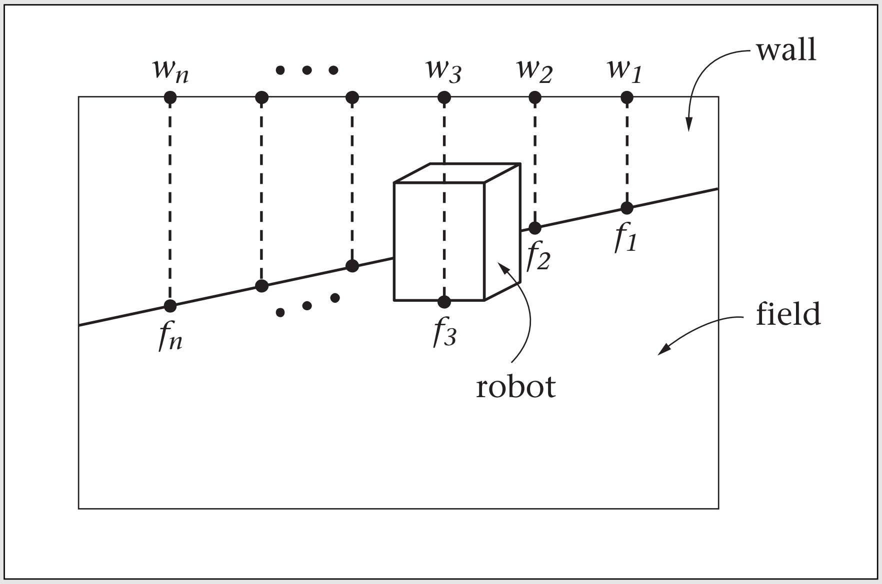


Figure C. An Illustration of a Robot View.
Straight lines $w_i f_i$ show the pass of water dropped from the top of the wall.

Conclusion

In a dynamically changing environment such as RoboCup, where most objects are moving around most of the time, we need near–real-time (25 frames a second) response from the robot vision system for fast decision making. Although the traditional methods of image processing for segmentation, edge detection, and object findings are very accurate,with the processing capabilities of PCs today, these methods are not able to respond in real-time speed. To overcome this processing speed problem, we preferred to have a nonexact, but reliable, solution to the vision problem.

Fast object detection was achieved by checking the color of pixels at jump points and defining a rectangular shape bounding box around each detected object. To simplify the calculations, the distance and angle of an object from the robot is estimated to be that of this rectangle.

Although we obtained satisfactory results from our method in real soccer robot competitions, we believe the combination of a CCD camera in front and an omnidirectional viewing system on top of the robot can give a more reliable performance, especially for localization.

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RoboCup rescue has many things in common with RoboCup soccer. It is a fully distributed, multiagent domain with hidden state, noisy sensors and actuators, and limited communication opportunities. RoboCup rescue introduces the challenges of scaling up to many more agents and coordinating multiple hierarchically organized teams.

In the competition, competing agents operate simultaneously in independent copies of the world. That is, they don't compete against each other directly but, rather, compare their performance under similar circumstances. The scoring metric is such that human lives saved is the most important measure, with injuries and building damage serving to break ties.

Seven teams competed in the 2001 RoboCup rescue competition. The winning team was YABAI from the University of Electro-Communications in Japan.

RoboCup Junior

RoboCup junior (figure 5) aims to develop educational methods and materials using robotics emanating from the RoboCup soccer theme. Following on the success of activities held at RoboCup-2000, this year, RoboCup Junior hosted 24 teams totaling nearly 100 participants from the local Washington area and other U.S. states as well as Australia, Germany, and the United Kingdom.

RoboCup Junior 2001, chaired by Elizabeth Sklar, included three challenges: (1) soccer, (2) rescue, and (3) dance. These categories are designed to introduce different areas within the field of robotics, such as operation within static versus dynamic environments, coordination in multiplayer scenarios, and planning with incomplete information. The challenges also emphasize both competitive and collaborative aspects for the teams, both within the games and throughout preparation. In particular, the dance challenge allows students to bring creativity in terms of art and music to an event that traditionally focuses on engineering.

Extensive feedback and analysis has been made through interviewing students and mentors who have participated in RoboCup junior events. This research by committee members and collaborators is ongoing and involves evaluation of the effectiveness of educational team robotics.

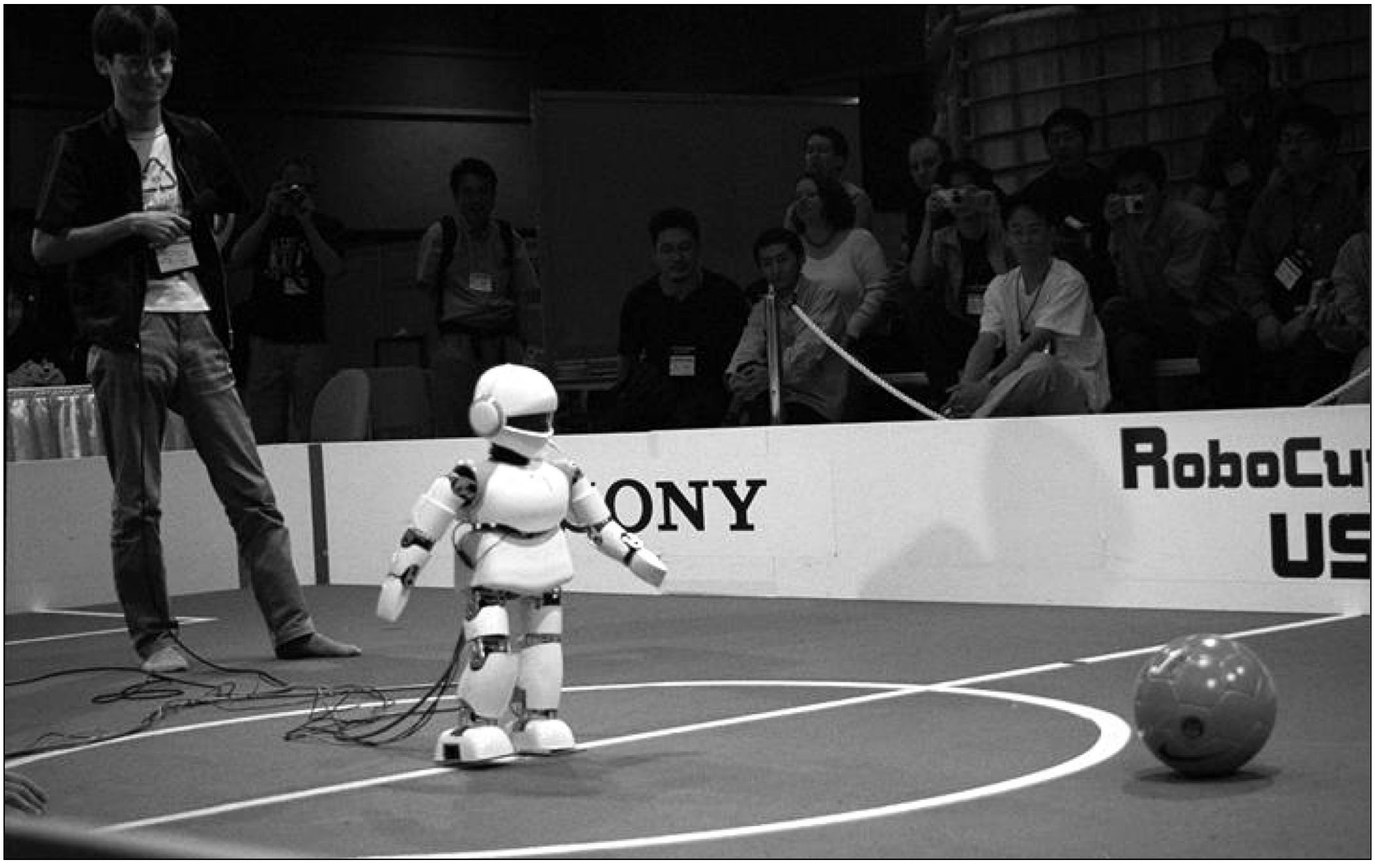

Figure 6. PINO*, the Humanoid Robot.*

Humanoid Exhibition

The humanoid exhibition, chaired by Dominique Duhaut, had only one participant—the PINO team—and received major attention. PINO is a small-size (70 centimeters in height) humanoid robot that can walk and follow the ball (figure 6). It was developed by ERATO Kitano Symbiotic Systems Project, which is a five-year government-founded project in Japan. A paper describing biped walking control for PINO won this year's Scientific Challenge Award for development of an energy minimum walking method (see the sidebar). An interesting feature of PINO is that it was designed to be open platform for humanoid research and only uses low-cost off-the-shelf components.[2]

Conclusion

RoboCup-2001 continued the ongoing, growing research initiative that is RoboCup. RoboCup-2002 will take place in June 2002 in Fukuoka, Japan, and Pusan, South Korea.[3]

Acknowledgments

We thank the full organizing committee of RoboCup-2001).[4] Special thanks to all the participating teams (see sidebar), without whom RoboCup would not exist. Thanks also to Elizabeth Sklar for input on the RoboCup junior section.

Notes

1. Mao Chen, Ehsan Foroughi, Fredrik Heintz, Spiros Kapetanakis, Kostas Kostiadis, Johan Kummeneje, Itsuki Noda, Oliver Obst, Patrick Riley, Timo Steffens, YiWang, and Xiang Yin. Users manual: RoboCup soccer server manual for SOCCER SERVER 7.07 and later. Available at http://sourceforge.net/projects/sserver/.

2. All technical information on PINO is now available under GNU General public licensing as OpenPINO platform PHR-001 (www.openpino.org/).

3. For more information, visit www.robocup. org.

4. See www.robocup.org/games/01Seattle/315.html) as well as the RoboCup executive committee (www.cs.cmu.edu/~robocup2001/robocup-federation.html

References

Gong, Y., and Sakauchi, M. 1995. Detection of Regions Matching Specified Chromatic Features. *Computer Vision and Image Understanding* 61(2): 163–269.

Soccer-Simulation League

11MONKEYS3, Keio University, Japan, Keisuke Suzuki
ANDERLECHT, IRIDIA-ULB, Belgium, Luc Berrewaerts
AT HUMBOLDT 2001, Humboldt University Berlin, Germany, Joscha Bach
A-TEAM, Tokyo Institute of Technology, Japan, Hidehisa Akiyama,
ATTUNITED-2001, AT& T Labs-Research, USA, Peter Stone
BLUTZLUCK, University of Leuven, Belgium, Josse Colpaert
CHAMELEONS'01, Carnegie Mellon University, USA, Paul Carpenter
CROCAROOS, University of Queensland, Australia, Mark Venz
CYBEROOS2001, CSIRO, Australia, Mikhail Prokopenko
DIRTY DOZEN, Institute for Semantic Information Processing, Germany, Timo Steffens
DRWEB (POLYTECH), State Technical University, Russia, Sergey Akhapkin
ESSEX WIZARDS, University of Essex, Huosheng Hu
FC PORTUGAL 2000, Universidades do Porto e Aveiro, Portugal, Luis Paulo Reis
FC PORTUGAL 2001, Universidade de Aveiro, Portugal, Nuno Lau
FCTRIPLETTA, Keio University, Japan, Norihiro Kawasaki
FUZZYFOO, Linkopings Universitet, Sweden, Mikael Brannstrom
GEMINI, Tokyo Institute of Technology, Japan, Masayuki Ohta
GIRONA VIE, University of Girona, Spain, Israel Muñoz
HARMONY, Hokkaido University, Japan, Hidenori Kawamura
HELLI-RESPINA 2001, Allameh Helli High School, Iran, Ahmad Morshedian
JAPANESE INFRASTRUCTURE TEAM, Future University-Hakodate, Japan, Hitoshi Matsubara
KARLSRUHE BRAINSTORMERS, Universitaet Karlsruhe, Germany, Martin Riedmiller
LAZARUS, Dalhousie University, Canada, Anthony Yuen
LIVING SYSTEMS, Living Systems, Germany, Klaus Dorer
LUCKY LUBECK, University of Lubeck, Germany, Daniel Polani
MAINZ ROLLING BRAINS, Johannes Gutenberg University, Germany, Felix Flentge
NITSTONES, Nagoya Institute of Technology, Japan, Nobuhiro Ito
OULU 2001, University of Oulu, Finland, Jarkko Kemppainen
PASARGAD, AmirKabir University of Technology, Iran, Ali Ajdari Rad
RMIT GOANNAS, RMIT, Australia, Dylan Mawhinney
ROBOLOG 2001, University of Koblenz, Germany, Frieder Stolzenburg
SALOO, AIST/JST, Japan, Itsuki Noda
SBCE, Shahid Beheshti University, Iran, Eslam Nazemi
SHARIF-ARVAND, Sharif University of Technology, Iran, Jafar Habibi
TEAM SIMCANUCK, University of Alberta, Canada, Marc Perron
TSINGHUAEOLUS, Tsinghua University, P. R. China, Shi Li
TUT-GROOVE, Toyohashi University of Technology, Japan, Watariuchi Satoki
UTUTD, University of Tehran, Iran, Amin Bagheri
UVA TRILEARN 2001, Universiteit van Amsterdam, The Netherlands, Remco de Boer
VIRTUAL WERDER, University of Bremen, Germany, Ubbo Visser
WAHOO WUNDERKIND FC, University of Virginia, USA, David Evans
WRIGHTEAGLE2001, University of Science and Technology of China, P. R. China, Chen XiaoPing
YOWAI2001, University of Electro-Communications, Japan, Koji Nakayama
ZENG01, Fukui University, Japan, Takuya Morishita

Rescue-Simulation League

ARIAN, University of Technology, Iran, Habibi Jafar Sharif
GEMINI-R, Tokyo Institute of Technology, Japan, Masayuki Ohta
JAISTR, Japan Advanced Institute of Science and Technology, Japan, Shinoda Kosuke
NITRESCUE, Nagoya Institute of Technology, Japan, Taku Sakushima
RESCUE-ISI-JAIST, University of Southern California, USA, Ranjit Nair
RMIT ON FIRE, RMIT University Australia, Lin Padgham
YABAI, University of Electro-Communications, Japan, Takeshi Morimoto

Small-Size Robot League

4 STOOGES, University of Auckland, New Zealand, Jacky Baltes
5DPO, University of Porto, Portugal, Paulo Costa
CM-DRAGONS'01, Carnegie Mellon University, USA, Brett Browning
CORNELL BIG RED, Cornell University, USA, Raffaello D'Andrea
FIELD RANGERS, Singapore Polytechnic, Singapore, Hong Lian Sng
FU FIGHTERS, Universitt Berlin, Germany, Sven Behnke Freie
FU-FIGHTERS-OMNI, Universitt Berlin, Germany, Raul Rojas Freie
HWH-CATS, College of Technology and Commerce, Taiwan, R.O.C., Kuo-Yang Tu Hwa Hsia
KU-BOXES2001, Kinki University, Japan, Harukazu Igarashi
LUCKY STAR II, Singapore Polytechnic, Singapore, Ng Beng Kiat
OMNI, Osaka University, Japan, Yasuhiro Masutani
OWARIBITO, Chubu University, Japan, Tomoichi Takahashi
ROBOROOS 2001, University of Queensland, Australia, Gordon Wyeth
ROBOSIX UPMC-CFA, University Pierre and Marie Curie, France, Ryad Benosman
ROGI TEAM, University of Girona, Spain, Bianca Innocenti Badano
ROOBOTS, The University of Melbourne, Australia, Andrew Peel
SHARIF CESR, Sharif University of Technology, Iran, Mohammad T. Manzuri
TEAM CANUCK, University of Alberta, Canada, Hong Zhang
TPOTS, Temasek Engineering School, Singapore, Nadir Ould Khessal
UW HUSKIES, University of Washington, USA, Dinh Bowman
VIPERROOS, University of Queensland, Australia, Mark Chang

Middle-Size Robot League

AGILO ROBOCUPPERS, Munich University of Technology, Germany, Michael Beetz
ARTISTI VENETI, Padua University, Italy, Enrico Pagello
CLOCKWORK ORANGE, University of Technology, The Netherlands, Pieter Jonker Delft
CMHAMMERHEADS'01, Carnegie Mellon University, USA, Tucker Balch
COPS STUTTGART, University of Stuttgart, Germany, Reinhard Lafrenz
CS FREIBURG, University of Freiburg, Germany, Bernhard Nebel
EIGEN, Keo University, Japan, Kazuo Yoshida
FUN2MAS, Politecnico di Milano, Italy, Andrea Bonarini
FUSION, Fukuoka University, Japan, Matsuoka Takeshi
GMD-ROBOTS, GMD-AIS, Germany, Ansgar Bredenfeld
ISOCROB, Instituto de Sistemas e Robtica, Portugal, Pedro Lima
JAYBOTS, Johns Hopkins University, USA, Darius Burschka
MINHO, University of Minho, Portugal, António Ribeiro
ROBOSIX, University Pierre and Marie Curie, France, Ryad Benosman
SHARIF CE, Sharif University of Technology, Iran, Mansour Jamzad
SPQR, University "La Sapienza," Italy, Luca Iocchi
THE ULM SPARROWS, University of Ulm, Germany, Gerhard Kraetzschmar
TRACKIES, Osaka University, Japan, Yasutake Takahashi

Sony Legged-Robot League

ARAIIBO, University of Tokyo, Japan, Tamio Arai
ASURA, Fukuoka Institute of Technology, Japan, Takushi Tanaka
BABYTIGERS 2001, Osaka University, Japan, Minoru Asada
CERBERUS, Bogazici University, Turkey, Levent Akin, and Technical Univ. of Sofia, Bulgaria, Anton Topalov
CMPACK'01, Carnegie Mellon University, USA, Manuela Veloso
ESSEX ROVERS, University of Essex, UK, Huosheng Hu
GERMAN TEAM, Humboldt University Berlin, Germany, Hans- Dieter Burkhard
LES 3 MOUSQUETAIRES, LRP, France, Pierre Blazevic
MCGILL REDDOGS, McGill University, Canada, Jeremy Cooperstock
ROBOMUTTS++, The University of Melbourne, Australia, Nick Barnes
SPQR-LEGGED, University "La Sapienza," Italy, Daniele Nardi
TEAM SWEDEN, Orebro University, Sweden, Alessandro Saffiotti
UNSW UNITED, University of New South Wales, Australia, Claude Sammut
UPENNALIZERS, University of Pennsylvania, USA, Jim Ostrowski
USTC WRIGHT EAGLE, University of Science and Technology of China, P. R. China, Xiaoping Chen
UW HUSKIES, University of Washington, USA, Dieter Fox

Robot Rescue League

EDINBURGH, University of Edinburgh, UK, Daniel Farinha
SHARIF-CE, Sharif University of Technology, Iran, Amir Jahangir
SWARTHMORE, Swarthmore College, USA, Gil Jones
UTAH, Utah State University, USA, Dan Stormont
MINNESOTA, University of Minnesota, USA, Paul Rybski
FLORIDA, University of South Florida, USA, Robin Murphy

Table 1. RoboCup 2001 Teams.

Gonzalez, R. C., and Woods, R. E. 1993. *Digital Image Processing*. Reading, Mass.: Addison-Wesley.

Jamzad, M.; Foroughnassiraei, A.; Chiniforooshan, E.; Ghorbani, R.; Kazemi, M.; Chitsaz, H.; Mobasser, F.; and Sadjed, S. B. 2000. Middle-Sized Robots: ARVAND. In *RoboCup-99: Robot Soccer World Cup II,* 74–84. Stockholm: Springer.

Kitano, H., and Asada, M. 1998. RoboCup Humanoid Challenge: That's One Small Step for a Robot, One Giant Leap for Mankind. In Proceedings of the International Conference on Intelligent Robots and Systems. Washington, D.C.: IEEE Computer Society.

Kitano, H.; Tambe, M.; Stone, P.; Veloso, M.; Coradeschi, S.; Osawa, E.; Matsubara, H.; Noda, I.; and Asada, M. 1997. The RoboCup Synthetic Agent Challenge '97. In Proceedings of the Fifteenth International Joint Conference on Artificial Intelligence, 24–29. Menlo Park, Calif.: International Joint Conferences on Artificial Intelligence.

McGeer, T. 1990. Passive Dynamic Walking. *International Journal of Robotics Research* 9(2): 62–82.

Noda, I.; Matsubara, H.; Hiraki, K.; and Frank, I. 1998. SOCCER SERVER: A Tool for Research on Multiagent Systems. *Applied Artificial Intelligence* 12:233–250.

Sangwine, S. J., and Horne, R. E. N. 1998. *The Colour Image-Processing Handbook*. New York: Chapman and Hall.

Stone, P. 2002. ATTUnited-2001: Using Heterogeneous Players. In *RoboCup-2001: Robot Soccer World Cup V,* eds. A. Birk, S. Coradeschi, and S. Tadokoro. Berlin: Springer Verlag. Forthcoming.

Yamasaki, F.; Endo, K.; Asada, M.; and Kitano, H. 2001. A Control Method for Humanoid Biped Walking with Limited Torque. Paper presented at the Fifth International Workshop on RoboCup, 7–10 August, Seattle, Washington.

Yamasaki, F.; Matsui, T.; Miyashita, T.; and Kitano, H. 2000. PINO, The Humanoid That Walks. In Proceedings of the First IEEE-RAS International Conference on Humanoid Robots. Washington, D.C.: IEEE Computer Society.

Yamasaki, F.; Miyashita, T.; Matsui, T.; and Kitano, H. 2000. PINO, the Humanoid: A Basic Architecture. Paper presented at the Fourth International Workshop on RoboCup, 31 August–1 September, Melbourne, Australia.

Manuela Veloso is associate professor of computer science at Carnegie Mellon University (CMU). She received her Ph.D. in computer science from CMU in 1992. She received a B.S. in electrical engineering in 1980 and an M.Sc. in electrical and computer engineering in 1984 from the Instituto Superior Tecnico in Lisbon. Veloso's long-term research goal is the effective construction of teams of intelligent agents where cognition, perception, and action are combined to address planning, execution, and learning tasks, in particular, in uncertain, dynamic, and adversarial environments. Veloso has developed teams of robotic soccer agents that have been RoboCup world champions in three different leagues, namely, simulation (1998, 1999), CMU-built small-wheeled robots (1997, 1998), and Sony four-legged dog robots (1998). Veloso is vice president of the RoboCup International Federation. She was awarded a National Science Foundation Career Award in 1995 and the Allen Newell Medal for Excellence in Research in 1997. Her e-mail address is veloso@cs.cmu.edu.

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