1 The Challenge of Robotic Soccer

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1.1 What is RoboCup?

RoboCup is the world championship in robotic soccer – it has been held every year since 1997. During a preliminary tryout in 1996, later called Pre RoboCup, the first "league" was formed: in the simulation league a team of 11 virtual players contends against another similar team. All action occurs in a simulated field managed by a computer. Later on, leagues of genuine robots were introduced: in the small-size league five robots play against another five in a field 2.9 meters long by 2.4 meters wide (size of the field as of 2002); in the mid-size league four robots play against four robots in a field 10 by 5 meters large (as of 2002). The main difference between both leagues is the size of the field, the size of the robots themselves, and its autonomy. In the small-size league the robots have a maximum diameter of 18 cm, in the mid-size league the maximum cross section of a robot is 50 cm. The small robots play using the information provided by a camera placed 3 meters above the field, whereas the mid-size robots carry their own cameras and other kinds of sensors. Starting in 1999, the Legged League was formed in which the Sony AIBO robotic dogs struggle three against three. Finally, in 2001 the first RoboCup rescue competition was held. Here, as in the simulation league, a virtual world is managed by a computer and teams compete trying to save virtual characters in a disaster scenario. The challenge consists in scheduling and managing scarce rescue resources in the most effective way. A humanoid league is planned for the immediate future. Robots resembling humans will then play against each other in order to reach the declared goal of the RoboCup initiative: to build robots that can beat the human world soccer champions by the year 2050.

Actually, most of the participants at the RoboCup competitions do not dare to think as far away as 2050. In the field of computer technology any prediction encompassing more than the next ten years is a risky proposition. The pace of technological development is such, that new applications and new hardware are emerging at a breathtaking pace. At the same time, however, we are far from understanding everything we would like to know about human intelligence and the human body. We cannot even fathom how much we will have to learn in order to build indisputably intelligent robots. Participants in RoboCup tournaments are more pragmatic, they are scientists eager to advance the state of the art in robotics, planning, scheduling, and multiagent systems research. So it happens that almost all RoboCup teams are sponsored by a university or research center. Typically the leader of each team is a senior researcher and the best part of the team is composed of students - graduates as well as undergraduates- eager to demonstrate their robots and expertise. In this sense, RoboCup is a scientific challenge and a benchmark for concepts and solutions developed to control autonomous robots.

At the same time, RoboCup has transformed into a limelight event, perhaps the best well-known robotic competition in the world. Of course, there are also the infamous RoboWars tournaments, held in the USA and the UK, where robots try to destruct each other. The big difference to RoboCup is, firstly, that in RoboCup no robots are destroyed, and secondly, that the robots are autonomous, they are not being remote controlled by humans. RoboCup is a peaceful event for the advancement of science.

Over the years, RoboCup has become a major happening attracting hundreds of the best robotics researchers in the world. Table 1 gives an overview of the evolution of participation in the RoboCup tournaments. Although RoboCup emerged as a side event to the International Joint Conference on Artificial Intelligence, it has overgrown its previous format and has become an event on its own right. Budgets for organizing the latest RoboCup competitions have run in the hundreds of thousands of dollars.

Table 1: Attendance to RoboCup events (number of teams in each league, 1997-2001)

Year	Total	Simulation	Small-Size	Mid-Size	Legged	Rescue
1997	41	32	4	5		
1998	62	34	12	16		
1999	73	35	18	20		
2000	84	40	16	16	12	
2001	105	44	20	18	16	7

Data from [Nebel 02]

1.2 Why RoboCup?

Robotic soccer, i.e. mobile autonomous robots playing this popular game, has become the new benchmark problem and holy grail in the field of Artificial Intelligence. First proposed in 1992, robotic soccer is becoming a public magnet and big business, with cities around the world vying years in advance for the privilege of holding the next competition. According to a press release issued during the RoboCup International Tournament held in Seattle during 2001, an estimated 3 million people followed the games and the results of the world championship. The competition in Japan during 2002 will be played in a baseball stadium built as a dome. However, even without this public interest, RoboCup is first and foremost big science, a new frontier for the Artificial Intelligence (AI) community.

AI research is concerned with all those tasks which humans solve almost subconsciously, but which are difficult to implement in computers, for example: speech and face recognition, bipedal walking, path planning in cluttered environments, etc. AI is also concerned with higher cognitive abilities, such as problem solving, theorem proving, computer algebra, or playing chess. Actually, the whole field was started mainly around the latter kind of "higher" problems which in the 1950s seemed to pose the greater challenge for researchers. Chess, particularly, was during many years the touchstone of AI research. Alan Turing, one of the founding fathers of the discipline, described as early as 1950 how to write a computer program to play the game. Chess appeared to be an ideal standardized problem, since the rules are well defined but the number of possible outcomes is so large that “intelligent” evaluation is needed if a computer is to win the game.

The 1980s, however, were a turning point in the history of AI. Researchers started to realize that chess and rule-based problems are not as difficult for the computer as they first seemed to be. Chess can be played by pure brute force, evaluating as many board positions per second as possible, without trying to imitate the board recognition abilities of a chess grand master. It was just a matter of time until even the world champion would lose to a computer. In May 1997, an IBM computer called Deep Blue won a chess tournament against Gary Kasparov, the reigning world champion. But even before this had happened, the AI community had started to move to greener pastures looking for a new "grand challenge" for the discipline. Since the 1980s, researchers such as Rodney Brooks from MIT, had been propagating the idea that "situated problem solving" was the real issue to be tackled by the AI community. Instead of solving toy problems, or problems in which the computer is isolated and abstracted from the world, the new challenge would be giving the computer a body (a robotic body), placing it in the real world and letting it solve non-trivial tasks. This came to be known as "embodied AI". It was in this spirit that some competitions arose, specially the first American Association for Artificial Intelligence Robotic Competition, held in San Jose in 1992. A robot had to navigate a course, interact with the public and solve some predefined tasks in a given order [Kortenkamp et al. 93]. But it was still a single robot, not a team.

Also in 1992, Alan Mackworth from the University of British Columbia in Canada, proposed to build robots for playing soccer. In his paper "On Seeing Robots", he states clearly what traditional "good old fashioned" AI has been missing and how limiting the assumptions underlying problem solving with computer agents are [Mackworth 92]. According to him, the main assumptions of traditional AI had always been:

- Knowledge is described as referring to individuals and relations among individuals.
- Belief is Knowledge: Agents beliefs are true and justified.
- Definite Knowledge: Agent's knowledge is definite and positive.
- Complete Knowledge: Knowledge of the world is complete, the closed world assumption isolates the task from the rest of the world.
- Static Environment: The environment is fixed, unless and agent changes it.
- One Agent: Only one active agent is in the world.
- Deterministic World: Agents can predict the consequences of their actions.
- Discrete Sequential Actions: Actions are discrete and are carried out one after the other.

For a game such as computer chess all these assumptions hold. This particular task can be solved, but once cracked by brute force it becomes irrelevant for handling more complex aspects of the real world in which none of the classical assumptions above hold. Mackworth proposed: "let us consider a world in which they are all violated [the assumptions above]. Suppose we want to build a robot to play soccer" [Mackworth 92]. Such a robot will be placed in a field, and it cannot assume that all its beliefs are true and justified. Its knowledge of the game situation is indefinite and incomplete. The environment is not static: the other robots move in unpredictable ways, robots can fail, the ball can go out of bounds. There is not a single agent, but many agents interacting with each other. The world is not deterministic, not even the rebound of the ball can be computed exactly. The game, played with many robots, arises from a combination of actions taken in parallel and actions have a continuous range (velocities, accelerations, rotations, etc). Therefore, robotic soccer is an ideal platform for investigating a setting in which all traditional assumptions of classical AI are violated. Yet, robotic soccer remains a "tractable problem", in the sense that it can be examined under standardized and reproducible conditions in a computer lab in the basement. It is not as difficult as sending a robot to walk the streets and it is not so expensive that AI researchers cannot afford the cost of actually building the machines,

At that time, AI researchers had been thinking for several years about new "grand challenges" for the field. In his presidential address to the American Association for Artificial Intelligence (AAAI) in 1988, Raj Reddy outlined several of them [Reddy 88]. The main differences between the different domains he considered were the amount of knowledge needed, the data rates, and the required response time. In computer chess, for example, the amount of encoded knowledge is low, the data rate too, and a response can be given within minutes. In robotics and computer vision tasks, however, the amount of knowledge needed and the data rate are both very high, while the response times must lay in the range of milliseconds. If we really want to consider building artificially intelligent systems, four conditions postulated by Allen Newell must hold, i.e. the system must operate in real time, must exploit vast amounts of knowledge, should be fault tolerant, and should learn. It turns out that robotic soccer is a better testbed for AI research as chess, and there are now much more AI researchers working on robotic soccer that on the old and revered game.

Every one which has participated in a RoboCup tournament knows it: robotic soccer is indeed a difficult problem. A successful team must address many different tasks in at least four areas: a) Computer vision: the robots must see their surroundings and infer the presence of other robots and the limits of the field; b) Communication: the robots must signal their intentions and beliefs to other members of the team, usually through a wireless link; c) Mechanics: the robots must be robust, must be fast and able to play after collisions, must be able to handle the ball; d) Coordination: the robots must play like a team, they must behave correctly. Each single problem often requires a group of two or three students who do the actual programming. And of course everything must be packed into a single system and must be fault-tolerant and efficient. RoboCup requires patience, lots of students, and many resources.

1.3 A Short History of RoboCup

Robotic soccer was an idea looking for its realization, and so it is not surprising that several people around the world arrived to similar conclusions as Mackworth at the beginning of the 1990s. In Tokyo, Japan, in particular, there had been a workshop on Grand Challenges on Artificial Intelligence in October 1992, of which there was a report at the 13th IJCAI held in the USA in 1993 [Kitano et al. 93]. Several new applications were identified as central benchmarks problems, one being the game of Go (which is much more complex than chess) and robotic soccer. In June 1993 a group including Hiroaki Kitano, Minoru Asada, Yasuo Kuniyoshi and others proposed to start a Robot J-League (for Japanese League, as the human soccer league is called in Japan) which almost immediately was transformed in the international event called RoboCup. In the USA, Peter Stone had seen Mackworth robots at a conference and began research in this direction with his advisor, Manuela Veloso, who then started a robotic soccer research group at Carnegie Mellon University.

In parallel to these discussions, Itsuki Noda from the Electrotechnical Laboratory (ETL) had finalized in September 1993 the first version of the soccer server program for the simulation league. The system was very crude, was written in an arcane programming language called MWP, and displayed the action on a character screen with 24 rows and 80 columns. The server underwent several transformations before it could be used: version 0 was rewritten in LISP in 1994, it displayed now the field in a graphics window, but using letters for each player. The next version was rewritten in C++ during 1995 and was demonstrated at IJCAI 95 [Noda 95]. Version 2 was written in 1996 and provided the simulation environment for Pre RoboCup 1996 in Osaka, Japan. The system was divided now into a soccer server (one for all teams) and a soccer client and monitor (one for each team). Many other programmers started collaborating at this stage and version 3, announced in February 1997, was used for the first RoboCup tournament in 1997.

The first wide public announcement of the RoboCup initiative was made in September 1993 and during IJCAI-95 it was decided that the first RoboCup tournament would be held in conjunction with IJCAI-97 in Nagoya, Japan [Kitano et al. 95]. As a preparation for this event, a Pre RoboCup tournament was held in 1996 during the International Conference on Intelligence Robotics and Systems (IROS) in Osaka. Eight teams competed in the simulation league and some actual robots were showed.

But there was Korea and researchers there were also active organizing their own robotic league. In September 1995, Jong Hwan Kim started the Micro-Robot World Cup Soccer Tournament (MiroSot). The first MiroSot competition was held in November 1996 in Korea with 23 teams from 10 countries. Mirosot tournaments followed then every year from 1997 to 2002, sometimes in the same country as the RoboCup events, as was the case in 1998 (France) and 2000 (Australia). However, in the MiroSot league only small robots compete, there is nothing similar to the mid-size robots used in RoboCup and there was no legged league until 2002. There is of course a kind of rivalry between MiroSot and RoboCup, each one claiming to be the World Cup on Robotic Soccer, but the RoboCup events have become much larger, are better organized and publicized as the MiroSot tournaments.

1.4 List of RoboCup Tournaments

Meanwhile, RoboCup can look back at the successful realization of five competitions. The tables below summarize the results of every event, showing the names and origin of the winning teams.

Pre RoboCup 1996 (Osaka, Japan)

Place	Simulation League
1	Tokyo U. Tokyo University Japan
2	Tokyo IT Tokyo Institute of Technology Japan
3	Waseda Waseda University Japan

RoboCup 1997 (Nagoya, Japan)

Place	Simulation	Small-Size	Mid-Size
1	AT-Humboldt 98 Humbodt University Germany	CMUnited Carnegie Mellon U. USA	Dream Team Univ. of Southern California USA
2	Andou Tokyo Institute of Technology Japan	MICROB University of Paris VI France	Ullanta Performance Robotics USA
3	Tambet et al University of South. California	ROGI University of Girona Spain	RMIT Raiders Royal Melbourne Inst. Of Tech. Australia

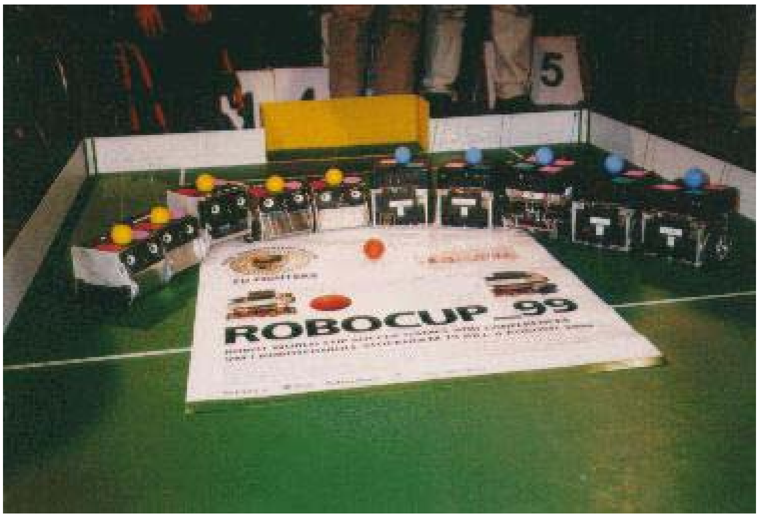
RoboCup 1998 (Paris, France)

Place	Simulation	Small-Size	Mid-Size
1	CMUnited	CMUnited 98	CS-Freiburg
	Carnegie Mellon U.	Carnegie Mellon U.	Freiburg University
	USA	USA	Germany
2	AT-Humboldt 98	RoboRoos	T-Team
	Humbodt University	University of Queensland	Tübingen University
	Germany	Australia	Germany
3	Amsterdam	5DPO/FEUP	Osaka

Corten and Rondema (University of Amsterdam)

RoboCup 1999 (Stockholm, Sweden)

Place	Simulation	Small-Size	Mid-Size	Legged
1	CMUnited 99	Big Red	CS Sharif	Les 3 Mousquetaires
	Carnegie Mellon University	Cornell University	Sharif University of Technology	Laboratoire de Robotique
	USA	USA	Iran	France
2	Magma Freiburg	FU Fighters	Azzurra Robot Team	UNSW United
	Freiburg University	Free University of Berlin	(several universities)	University of New South Wales
	Germany	Germany	Italy	Australia
3	Essex Wizards	Lucky Star	CS Freiburg	CMTrio 99
	Essex University	Nee Ann Polytechnic	Freiburg University	Carnegie Mellon University
	UK	Singapore	Germany	USA



RoboCup 2000 (Melbourne, Australia)

Place	Simulation	Small-Size	Mid-Size	Legged
1	FC Portugal Univ. de Averiro & do Porto Portugal	Big Red Cornell University USA	CS Freiburg Freiburg University Germany	UNSW United University of New South Wales Australia
2	Karlsruhe Brainstormers Karlsruhe University Germany	FU Fighters Free University of Berlin Germany	Golem Team (autonomous team) Italy	Les 3 Mousquetaires Laboratoire de Robotique France
3	AT&T-CMU 2000 Carnegie Mellon & AT6T USA	Lucky Star Nee Ann Polytechnic Singapore	CS Sharif Sharif University of Technology Iran	CM Pack 00 Carnegie Mellon University USA

RoboCup 2001 (Seattle, USA)

Place	Simulation	Small-Size	Mid-Size	Legged
1	Tsinghuaeolus Tsinghua University China	Lucky Star Nee Ann Polytechnic Singapore	CS Freiburg Freiburg University Germany	UNSW United University of New South Wales Australia
2	Karlsruhe Brainstormers Karlsruhe University Germany	Field Rangers Singapore Polytechnic Singapore	Trackies Osaka University Japan	CM Pack 01 Carnegie Mellon University USA
3	FC Portugal 2001 Univ. de Aveiro & do Porto Portugal	Big Red Cornell University USA	Eigen Keio University Japan	Upennalizers University of Pennsylvania USA

Rescue Simulation League 2001

1. YabAI, University of Electro-Communications, Japan
2. Arain, Sharif University of Technology, Iran
3. Rescue-ISI-JAIST, University of Southern California, USA

RoboCup 2002 (Fukuoka, Japan)

Place	Simulation	Small-Size	Mid-Size	Legged
1	Tsinghuaeolus Tsinghua University China	Big Red Cornell University USA	CS Freiburg Freiburg University Germany	UNSW United University of New South Wales Australia
2	Karlsruhe Brainstormers Karlsruhe University Germany	FU-Fighters Free University Berlin Germany	Trackies Osaka University Japan	CM Pack 01 Carnegie Mellon University USA
3	FC Portugal 2001 Univ. de Aveiro & do Porto Portugal	Lucky Star Nee Ann Polytechnic Singapore	Eigen Keio University Japan	Upennalizers University of Pennsylvania USA

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