systems[2].

Prior to conducting the research reported in this chapter, we used neural networks to teach an agent to shoot a moving ball into a goal in a simulator based closely upon the Dynasim system [Sahota 96]. The simulator models the non-holonomic wheeled Dynamite robots [Sahota *et al.* 95]. In this scenario, we were able to use one neural network to time the agent's approach towards the ball, and another to aim the ball. The learned behavior successfully enabled the agent to redirect a moving ball with varying speeds and trajectories into specific parts of the goal. By carefully choosing the input representation to the neural networks so that they would generalize as much as possible, the agent was able to use the learned behavior in all quadrants of the field even though it was trained in a single quadrant [Stone and Veloso 98d].

Learning was applied in both simulated and real robotic, to hit a stationary ball into the goal using the concept of learning from easy missions [Asada *et al.* 94a]. By first placing the ball directly in front of the goal and then gradually moving it farther away, thus making the task harder, the learning time was reduced from exponential to linear in the size of the state space within an RL framework. The robots achieved 70% success in simulation and 40% success in the real world.

Another early example of learning an individual skill in the RoboCup soccer server involved using a neural network to enable an agent to learn when to shoot and when to pass [Matsubara *et al.* 96]. An agent was given the ball near the opponent's goal with a goaltender blocking the way and a teammate nearby. Based on the positions of the ball, the goaltender, and the teammate, the agent with the ball learned when it was best to shoot directly at the goal and when it was best to pass.

In a similar setup, using the same Dynasim-based simulator mentioned above, we used memory-based learning to allow an agent to learn when to shoot and when to pass the ball [Stone and Veloso 96a]. This learning was of an individual skill since the goaltender and the teammate used deterministic, fixed behaviors.

[2] A full discussion of related robotic soccer systems, including more recent learning approaches, appears in Chapter 9 (Section 9.2).

Chapter 8

Competition Results

In Chapters 3–7, I presented the main contributions of this thesis along with extensive controlled experiments empirically validating each individual contribution. However, since the overall goal is to a create a complete team of agents that can operate in an adversarial environment, it is also interesting and informative to note how the team performs against a wide range of previously-unseen adversaries.

This chapter documents our experiences at several robotic soccer competitions in which we have participated over the years. Since competitions are not controlled experiments, their results are not presented as scientific validation of our individual techniques. Such validation is presented in the previous chapters. However, I believe that competition results provide useful evaluations of complete systems. In addition, I believe that qualitative evaluations and anecdotes from these competitions teach some valuable lessons and provide insights into the strengths and weaknesses of various approaches.

We named all of the teams that we entered in competitions "CMUnited." In this chapter, I differentiate among the teams based on the year and platform in which they competed. For example, the "CMUnited-96 simulator team" competed in the simulator competition in 1996; the "CMUnited-97 small-robot team" competed in the small-robot competition in 1997.

No individual team that we entered in a competition embodies all of the research contributions of this thesis. The team member agent architecture is used in several of the teams, while TPOT-RL is used in none: it requires more training against an opponent than is possible in competitions. Throughout this chapter, I indicate which techniques are used by each team and Table 8.1 summarizes the correspondence between teams and techniques. Although set-plays (Section 3.3.3) and SPAR (Section 3.5.2) are presented in Chapter 3 as part of the flexible teamwork structure, they are given separate entries in the table since they are both used outside of the teamwork structure by at least one team.

Sections 8.1–8.4 provide match results and anecdotes from 4 competitions in which we participated. Section 8.5 concludes with the most important lessons learned from these competitions.

CMUnited Team (year/platform)	Team Member Agent Arch.	Comm. Paradigm	Teamwork Struct.	Set-Plays	SPAR	Learned Ball Intcpn. (NN)	Learned Pass Eval. (DT)
96/simulator						+	
96/robots				+			
97/simulator	+	+	+	+		+	+
97/robots	+		+	+			
98/simulator	+	+	+	+	+		+
98/robots	+				+		

Table 8.1: The research techniques used by the various CMUnited teams which we entered in competitions.

8.1 Pre-RoboCup-96

The first robotic soccer competition of any sort was held on November 5–7, 1996 in Osaka, Japan [Kitano 96]. In conjunction with the IROS-96 conference, Pre-RoboCup-96 was meant as an informal competition to test the RoboCup soccer server in preparation for RoboCup-97. Most of the entrants were from the Tokyo region and were in frequent contact with the developer of the soccer server.

At the time of the competition, we had only begun our agent development, having created nothing more than the learned ball-interception behavior described in Chapter 5. In last-minute preparation for the event, we developed a static team formation and a fixed, hand-coded receiver choice function (RCF) similar to the prefer right wing (PRW) RCF defined in Section 6.3.1. The player closest to the ball always moved towards it and then passed to a pre-determined teammate, with one designated player shooting towards the goal.

We were aware at the time that our CMUnited-96 simulator team implementation was preliminary, but we entered the competition in order to attain a feeling for what areas needed the most attention, and to help test the soccer server. Table 8.2 shows the results of the games in which CMUnited-96 participated.

Opponent	Affiliation	Score (CMU–Opp.)
Oota	Tokyo Institute of Technology, Japan	4 – 1
ETL	Electrotechnical Laboratory, Japan	7 – 0
Sekine	Tokyo Institute of Technology, Japan	1 – 13
Ogalets	Tokyo University, Japan	1 – 9
Waseda	Waseda University, Japan	3 – 4*
TOTAL		16 – 27

Table 8.2: The scores of CMUnited-96's games in the simulator league of Pre-RoboCup-96. CMUnited-96 won 2 of its 5 games, finishing in 4th place out of 8 teams. *The last game was lost by one goal in overtime.

An important lesson learned at this competition was that it is very important to be able to get to the ball quickly and efficiently. The two top teams, Ogalets and Sekine, each had several players quickly moving towards the ball, thus increasing the likelihood that they would retain possession. Our preliminary strategy of having a single player moving slowly and deliberately towards the ball proved to be ineffective. The trained neural network was good at blocking the ball, but there was no incentive built into the training regime to get to the ball quickly. We learned at this competition that robot soccer teams must have either very efficient ball-interception, or several players moving towards the ball at once. In later competitions, we aimed to improve ball-interception efficiency, while also occasionally sending multiple players towards the ball.

8.2 MiroSot-96

The first robotic soccer competition involving real robots was held immediately after Pre-RoboCup-96, on November 9–12, 1996 in Taejon, South Korea [Kim 96]. Called MiroSot-96, 19 robotic teams competed in this tournament. As a single elimination tournament, it provided for only a single game for many of the teams, including CMUnited-96, which was matched in its first game against the eventual runner-up.

MiroSot-96 required smaller robots than the ones described in Section 2.3 (7.5cm^3 maximum). In addition, there were only three allowed per team. The robots we used in this competition were a preliminary version of those described in Section 2.3 [Achim *et al.* 96]. Although they did not use the team member agent architecture or any of the machine learning techniques described in this thesis, they did include complex set-plays.

Table 8.3 shows the result of our single game at the MiroSot-96 competition. The Miro team ended up losing in the finals 20–0 to the team from NewtonLabs, USA.

Opponent	Affiliation	Score (CMU–Opp.)
Miro	Korean Advanced Institute of Science and (KAIST)	3 – 7
TOTAL		3 – 7

Table 8.3: The score of CMUnited-96's game in the robot league of MiroSot-96. CMUnited-96 lost its only game.

The winner of MiroSot-96, NewtonLabs, dominated at this tournament due mostly to the speed of its vision system and robots [Sargent *et al.* 97]. At this tournament we learned the importance of the vision component of robotic soccer systems.

In addition to the 3-robot competition, MiroSot-96 also included a single robot competition: each team was allowed just a single robot on the field. In this competition, the CMUnited-96 robot lost in the finals by one goal. Table 8.4 shows the results of the two games in which it competed.

Opponent	Affiliation	Score (CMU–Opp.)
Rogi	University of Girona, Catalonia, Spain	4 – 2
Lami	Federal Institute of Technology, Switzerland	4 – 5
TOTAL		8 – 7

Table 8.4: The scores of CMUnited-96's games in the single robot league of MiroSot-96. CMUnited-96 won 1 of its 2 games, finishing in 2nd place out of 4 teams.

8.3 RoboCup-97

RoboCup-97 was the first formal RoboCup championship. It was held on August 23–29, 1997 in Nagoya, Japan in conjunction with the IJCAI-97 conference [Kitano 98]. At RoboCup-97, we entered both the simulator competition and the small-robot competition.

8.3.1 Simulator Competition

The RoboCup-97 simulator competition was the first formal simulated robotic soccer competition. With 29 teams entering from all around the world, it was a very successful tournament.

It was in preparation for this competition that the team member agent architecture, including both the flexible teamwork structure and the inter-agent communication paradigm, described in Chapter 3 was developed. In addition to the team member agent architecture, the CMUnited-97 simulator team which entered this competition used the learned ball-interception and pass-evaluation skills. In particular, the decision tree (DT) RCF presented in Section 6.3.1 was used.

Table 8.5 shows the results of CMUnited-97's games in this tournament. CMUnited-97 won 3 of its first 4 matches by wide margins, with the other match being a close victory. Its 5th opponent, FCMellon, was also our own team and was identical to CMUnited except that it did not use a flexible teamwork structure: players did not switch positions, did not use flexible positioning of any sort, and did not use set-plays. Our goal in entering FCMellon in the competition was to highlight the impact of our research contributions in CMUnited. Due to the results reported in Section 3.6, we expected CMUnited to win this game. Before the game between CMUnited and FCMellon, FCMellon won its 4 games by a combined score of 49–4.

The subsequent game was against the eventual tournament champion AT-Humboldt. As described in Section 3.6, CMUnited-97 used a 4-4-2 formation in general, switching to an 8-2-0 formation if winning near the end of the game, or a 3-3-4 formation if losing. The triggers for these formation switches were defined as part of the locker-room agreement. However, by the time CMUnited-97 played against them, it was clear from watching other games that AT-Humboldt was the team to beat. Therefore, we altered the team's locker-room agreement so that it would adopt a more conservative, defensive strategy at the beginning of the game. As a result, AT-Humboldt scored fewer goals against CMUnited-97 than it did against any of its other competitors. The 6–0 result might have been closer had CMUnited-97 not automatically switched to the more offensive 3-3-4 formation near the end of the game when it was losing in an attempt, though unsuccessful, to score some goals.

Opponent	Affiliation	Score (CMU–Opp.)
LAI	Universidad Carlos III De Madrid, Spain	9 – 1
RM Knights	Royal Melbourne Inst. of Tech., Australia	16 – 0
Kinki	Kinki University, Japan	6 – 5
Team Garbage Collectors	Justsystem, Japan	24 – 0
FCMellon	Carnegie Mellon University, USA	6 – 0
AT-Humboldt	Humboldt University of Berlin, Germany	0 – 6
ISIS	Information Sciences Institute (USC), USA	1 – 2*
TOTAL		62 – 14

Table 8.5: The scores of CMUnited-97's games in the simulator league of RoboCup-97. CMUnited-97 won 5 of its 7 games, finishing in 4th place out of 29 teams. *The last game was lost by one goal in overtime.

One of the main advantages of the AT-Humboldt team was its ability to kick the ball harder than any other team. Its players did so by kicking the ball around themselves, continually increasing its velocity so that it ended up moving towards the goal faster than was imagined possible. Since the soccer server did not enforce a maximum ball speed, a property that was changed immediately after the competition, the ball could move arbitrarily fast, making it impossible to stop. With this advantage at the low-level behavior level, no team, regardless of how strategically sophisticated, was able to defeat AT-Humboldt.

Having lost in the semi-finals, CMUnited-97 then played in the 3rd-place game against ISIS. CMUnited-97 scored first in this game off of a corner-kick set-play. However, ISIS equalized near the end of the game and the game went to overtime. ISIS scored to win in what proved to be one of the more exciting matches of the tournament.

The RoboCup-97 simulator competition was won by the team that found the best domain-dependent solutions, moving and kicking better than the other teams. However, this team's success alerted other teams to the necessity of solving the low-level problems. At the subsequent competition, RoboCup-98, there were several teams with roughly equal low-level skills, thus allowing the high-level, more MAS-research-based solutions to make the key differences.

8.3.2 Small-Robot Competition

As described in Section 3.7, our team member agent architecture—including the teamwork structure and set-plays— while developed in simulation, was also used by the CMUnited-97 real robots which won the RoboCup-97 small-robot competition [Veloso *et al.* 98a]. Table 8.6 shows the results of the games at RoboCup-97.

In total, CMUnited-97 scored thirteen goals, allowing only one against. The one goal against was scored by the CMUnited goaltender against itself, though under an attacking situation from MICROB. We refined the goaltender's behavior as presented in Appendix B (Section B.2.4), following the observation of our goaltender's error.

As the CMUnited-97 small-robot matches proceeded, spectators noticed many of the team behaviors described in Chapter 3. The robots switched positions during the games,

Opponent	Affiliation	Score (CMU–Opp.)
NAIST	Nara Institute of Science and Technology, Japan	5 – 0
MICROB	University of Paris VI , France	3 – 1
Girona U.	University of Girona, Catalonia, Spain	2 – 0
NAIST	Nara Institute of Science and Technology, Japan	3 – 0
TOTAL		13 – 1

Table 8.6: The scores of CMUnited-97's games in the small-robot league of RoboCup-97. CMUnited-97 won all 4 games, finishing in 1st place out of 4 teams.

and there were several successful passes. The most impressive goal of the tournament was the result of a 4-way passing play: robot 1 passed to robot 2, which passed back to robot 1; then robot 1 passed to a third robot, robot 3, which shot the ball into the goal.

Like in the simulator competition, this first RoboCup small-robot competition was won by the team with the best low-level sensing and acting abilities. No other team had the reliable vision or skills exhibited by the CMUnited-97 robots. However, also like in the simulator competition, CMUnited-97's success alerted other teams to the importance of these low-level abilities, leading to a competition among several more equally-skilled teams the following year.

8.4 RoboCup-98

The second international RoboCup championship, RoboCup-98, was held on July 2–9, 1998 in Paris, France [Asada and Kitano 99]. It was held in conjunction with the ICMAS-98 conference. As mentioned in Section 8.3, the winners of both the simulator and small-robot competitions at RoboCup-97 had much better low-level skills than the other teams and won easily. At RoboCup-98, both the simulator and small-robot competitions had much closer matches among the best teams. CMUnited-98 won both of these competitions due to a combination of good low-level and high-level strategic reasoning.

8.4.1 Simulator Competition

As one of the main contributions of this thesis, The CMUnited-98 simulator team is fully specified in Section 3.5 and Appendix B, Section B.1. It uses the team member agent architecture, including the teamwork structure, communication paradigm, set-plays, and SPAR, and a trained decision tree for pass evaluation. At the RoboCup-98 simulator competition, CMUnited-98 won all 8 of its games by a combined score of 66–0, finishing 1st in a field of 34 teams. Table 8.7 details the game results.

From observing the games, it was apparent that the CMUnited-98 low-level skills were superior in the first 6 games: CMUnited-98 agents were able to dribble around opponents, had many scoring opportunities, and suffered few shots against.

However, in the last 2 games, the CMUnited-98 strategic formations, communication, and ball-handling routines were put more to the test as the Windmill Wanderers (3rd place)

Opponent	Affiliation	Score (CMU–Opp.)
UU	Utrecht University, The Netherlands	22 – 0
TUM / TUMSA	Technical University Munich, Germany	2 – 0
Kasuga-Bitos II	Chubu University, Japan	5 – 0
Andhill'98	NEC, Japan	8 – 0
ISIS	Information Sciences Institute (USC), USA	12 – 0
Rolling Brains	Johannes Gutenberg-University Mainz, Germany	13 – 0
Windmill Wanderers	University of Amsterdam, The Netherlands	1 – 0
AT-Humboldt'98	Humboldt University of Berlin, Germany	3 – 0
TOTAL		66 – 0

Table 8.7: The scores of CMUnited-98's games in the simulator league of RoboCup-98. CMUnited-98 won all 8 games, finishing in 1st place out of 34 teams.

and AT-Humboldt'98 (2nd place) also had similar low-level capabilities. In these games, CMUnited-98's abilities to use set-plays to clear the ball from its defensive zone, to get past the opponents' offsides traps, and to maintain a cohesive defensive unit became very apparent. Many of the goals scored by CMUnited-98 were a direct result of the opponent team being unable to clear the ball from its own end after a goal kick: a CMUnited-98 player would intercept the clearing pass and quickly shoot it into the goal. In particular, two of the goals in the final game against AT-Humboldt'98 were scored in this manner. On the other hand, the CMUnited-98 simulator team was able to clear the ball successfully from its own zone using its ability to execute set-plays, or pre-compiled, multi-agent plans (see Section 3.5.2). Rather than kicking the ball up the middle of the field, one player would pass out to the sideline to a second player that would then clear the ball up the field. After a series of 3 or 4 passes, the ball was usually safely in the other half of the field.

Another strategic advantage that was clear throughout CMUnited-98's games was the players' abilities to maintain a coherent defensive unit exploiting the offsides rule, and conversely, its ability to get through the defense of other teams. Often, the opposing teams were unable to get anywhere near the CMUnited-98 goal because of the defenders' ability to stay in front of some of the opposing forwards, thus rendering them offsides and prohibiting them from ever successfully receiving the ball.

In order to deal with opposing teams that tried to use a similar technique, the CMUnited-98 forwards would kick the ball towards the offensive corners of the field (the "sending" skill described in Appendix B, Section B.1.7) and then either get to the ball before the defenders or intercept defenders' clearing passes. CMUnited-98 scored several goals after such kicks to the corners.

In addition to the strategic reasoning that helped the team win its final two games, the fine points of the dribbling and goaltending skills also came into play. Using their predictive, locally optimal skills (PLOS—see Section 3.5.1), the CMUnited-98 players were occasionally able to dribble around opponents for shots. At a crucial moment against the Windmill Wanderers, the CMUnited-98 goaltender made a particularly important save: while winning 1–0 near the end of the game, a shot got past the goaltender, but it was able to turn and catch the ball before the ball entered the goal.

8.4.2 Small-Robot Competition

Like in the simulator competition, the RoboCup-98 small-robot competition featured matches against several teams with similar low-level sensing and acting abilities. Since the CMUnited-97 small-robot team is more reflective of the contributions of this thesis than the CMUnited-98 small-robot team, it is the CMUnited-97 small-robot team that is described in Section 3.7 and Appendix B, Section B.2. However, CMUnited-98 uses both the team member agent architecture and SPAR (see Section 3.5.2, which was developed in parallel both in simulation and on the real robots. Table 8.8 shows the scores of the games of the CMUnited-98 small-robot team.

Opponent	Affiliation	Score (CMU–Opp.)
iXS	iXs Inc.	16 – 2
5DPO	University of Porto, Portugal	0 – 3
Paris-8	University of Paris-8	3 – 0
Cambridge	University of Cambridge, UK	3 – 0
Roboroos	University of Queensland, Australia	3 – 1
TOTAL		25 – 6

Table 8.8: The scores of CMUnited-98's games in the small-robot league of RoboCup-98. CMUnited-98 won 4 of its 5 games, finishing in 1st place out of 11 teams.

In the second match, against 5DPO, we experienced the brittleness of low-power radio communication in public places. In this match, CMUnited-98 performed miserably, often just turning in circles. We think that this failure occurred because of radio interference. After identifying and eliminating a possible source of interference, CMUnited-98 was able to resume its successful performance.

The final two games, against Cambridge and Roboroos, were both close matches against teams with similar sensing and acting capabilities to those of CMUnited-98. The key to CMUnited-98's success was its strategic play, including sophisticated goaltending, defending, and collaborative attacking using SPAR.

8.5 Lessons Learned from Competitions

Robotic soccer competitions have the potential to accelerate scientific progress within the robotic soccer domain. However, there are also many potential hazards that can render them detrimental to progress. By participating in the competitions described in Sections 8.1–8.4, we learned many things, both about competitions themselves and about our own research.

RoboCup, one of the main robotic soccer organizations and the one with which I am most closely associated, is primarily a research initiative. As such, the goal of the entire organization is to help advance the state of the art. It has certainly done so by providing new and challenging domains for studying issues within robotics and AI, such as "design principles of autonomous agents, multi-agent collaboration, strategy acquisition, real-time reasoning and planning, intelligent robotics, sensor-fusion, and so forth" [Kitano *et al.* 97].

However, the domains exist without the competitions. In this section, I examine the potential hazards and potential benefits of having periodic large-scale robotic soccer competitions, drawing on our experiences as participants. I operate under the premise that scientific progress (as opposed to, for example, entertainment) is the primary goal.

I start, in Section 8.5.1, by examining the potential hazards of competitions. Then, in Section 8.5.2, I point out the potential benefits. As many potential hazards and benefits are quite similar, it is up to the participants and organizers to sway the balance towards the benefits.

8.5.1 Hazards

There are many potential hazards to scientific progress involved in holding organized robotic soccer competitions. However, many can be avoided through careful organization of the competitions along with an engineered social climate within the community. Here, I list the possible hazards while, where possible, indicating how RoboCup has tried to avoid them.

Obsession with winning. One of the most obvious potential hazards of competitions is that people try to win them at the expense of all else, including science. Especially if there are monetary prizes involved, many people will focus only on winning and there is a potential incentive to keep successful techniques secret from year to year. RoboCup does its best to avoid this hazard by not awarding any monetary prizes. In addition, "scientific challenge" awards are given to teams who, in the opinions of the organizers, have demonstrated the best scientific contributions in their teams. In comparison with the competition winners, winners of these scientific challenge awards are given equal, if not greater, status at the awards ceremonies and within the community. Thus, there is explicit incentive given to deemphasize winning in favor of focusing on scientific contributions. Nonetheless, competitive spirit can easily take over.

Domain-dependent solutions. Another potential hazard of competitions, particularly within complex domains, is that it can be difficult to avoid getting bogged down in the low-level details of the domain. If the competition is to serve scientific interests, the winning solutions should be ones that are generally applicable beyond the particular domain in question. Of course, it is impossible to avoid requiring some domain-dependent solutions. However, while necessary, they should not be sufficient to produce a winning team. One way to encourage an emphasis on high-level, generalizable solutions is to repeat the same competition several times. While the first iteration is likely to be won by the best domain-dependent solution, subsequent events are more likely to find several teams using the same low-level approach that has already been proven effective. Then the difference among the teams will be more at the general levels. For example, at RoboCup-97, the winning teams in both the simulator and small-robot competitions were the ones that had the best low-level sensing and acting capabilities. However at RoboCup-98, there were several teams with similar low-level capabilities. Instead, the crucial differences were at the level of collaborative and adversarial strategic reasoning using techniques, such as those described in this thesis, that are not limited to the robotic soccer domain.

Cost escalation. Especially in the robot competitions, there is the potential to have increasingly expensive solutions. If an expensive technology provides a significant advantage at one competition, then it might become a prerequisite for success in future years. If the expense is prohibitive to academic researchers, then the competition could die out. This issue has not yet been addressed in RoboCup. One possible solution would be to require that all teams use a common hardware platform, restricting the differences to the software. In fact, the RoboCup-98 legged robot competition used this approach as the only robots meeting the competition specifications were the Sony legged robots [Veloso *et al.* 98c]. However, in general, this is not a satisfactory approach for RoboCup given that some of the interesting research issues are in the creation of the hardware itself. Another possible solution would be to enforce cost limits on entrants. However, such a restriction would be very difficult to define and enforce adequately. Cost escalation may become a serious issue for RoboCup in the near future.

Restrictive rules. While it is important to have well-defined rules for competitions, there is a potential to discourage research innovations via these rules. Especially for competitions involving robots, it is difficult to create rules that do not have loopholes but that are not overly restrictive. RoboCup's approach has been to make the rules flexible enough to allow for a wide variety of robot-design decisions. The inevitable rules disputes are then handled as amicably as possible in a spirit of cooperation at the competitions. While this approach has the potential to lead to some very heated arguments, it is the best from a research perspective.

Invalid evaluation conclusions. There is the potential at competitions to conclude that if team A beats team B, then all of the techniques used by team A are more successful than those used by team B. However, this conclusion is invalid. Unless the teams are identical except in one respect, no individual aspect of either team can conclusively be credited with or blamed for the result. Indeed, the CMUnited team won several of the competitions described above, but I do not present this chapter as an evaluation of any of the general thesis contributions other than the team as a whole. Instead, we conduct extensive controlled experiments to validate our research contributions.

8.5.2 Benefits

While there are many potential hazards to holding robotic soccer competitions, there are also many potential benefits. Here I list the possible benefits, again illustrating them with specific examples from RoboCup whenever possible.

Research Inspiration. While one potential hazard of competitions stemming from peoples' competitive spirit is an obsession with winning, a related benefit is that competitions are a great source of research inspiration. Several of the innovations reported in this thesis, most significantly the entire team member agent architecture, are the direct result of preparations for one of the above competitions. While they started as innovative solutions to challenging specific problems, we were then able to abstract their contributions into general frameworks. The natural desire to win is a strong motivation to create a good team by solving the challenging aspects of the domain.

Deadlines for creating complete agents. Competitions create hard deadlines for the creation of *complete* working systems. In order to compete, it is not sufficient for any one component of the system to be operational. Therefore, entrants must confront the challenging issues of "closing the loop," i.e. getting all components working from sensing, to acting, to strategic reasoning. They must create complete agents. No matter how sophisticated a team's high-level strategic reasoning, if it does not solve the low-level issues, some other team will easily win. Our experience has been that these deadlines have forced us to solve difficult holistic problems that we might have otherwise overlooked: these problems have been a source of research inspiration for us.

Common platform for exchanging ideas. Robotic soccer competitions bring together a group of people who have all tried to solve the same problems in the same domain. Unlike in many research communities, there is a common substrate system and a common language among participants. For example, in the planning community [Simmons *et al.* 98], researchers use a wide variety of planning systems, each with its own properties and idiosyncrasies, sometimes making it difficult to directly compare approaches and technique. In RoboCup, on the other hand, everyone implements their ideas in the same underlying architecture. Consequently, it is relatively easy to compare the various systems.

Continually improving solutions. When holding repeated competitions with the same platform, there is likely to be a continual improvement in solutions from event to event. All entrants know that in order to have a chance of winning a competition, they must be able to outperform the previous champion. Therefore, they are motivated to find some method of improving over the previous solutions. Of course, this benefit only applies if the same, or similar, rules are used as the basis for competition year after year. For example, in the AAAI robot competitions [Arkin 98], there are new tasks to be solved every year. While the new tasks encourage new entrants, there is no basis for directly measuring improvement from year to year.

Excitement for students at all levels. The inherent excitement of the robotic soccer competitions encourages students at all levels to become involved in serious research. Competition entries often come from large teams of professors, graduate students, and undergraduates working together. By encouraging more people to become involved in the research, the competitions can speed up progress.

Wide pool of teams created. After each competition, all of the entrants have created teams capable of performing in the given domain. If these teams are made available in some way, they can subsequently be used for controlled testing of research contributions. For example, in order to test technique x that is a single aspect of one's team, one could play the team against another team first with technique x active, and then without, thus establishing the effects of technique x. While such testing could be done against any team, it is often up to the researchers themselves to create the team against which to test. As a result the comparison is often done against a trivial or simple team. The competition can provide several teams against which to test, each of which is the result of serious effort by an independent group of researchers.

Encourage flexible software and hardware. Taking one's system out of one's own lab and into a new setting, whether it be a software system that is to be run on different computers or a robotic system that is to be run under different environmental conditions, requires a certain degree of flexibility in the system's creation. For example, rather than creating a vision system that works only in the lighting conditions in one's own lab, researchers must create a system that is easily adaptable to new conditions. Thus, the competition encourages general solutions that are more likely to apply in a wide variety of circumstances.

It has been our experience so far that the benefits of robotic soccer competitions outweigh the hazards. Most significantly as a strong source of research inspiration, robotic soccer competitions have played an important role in my thesis research. Again, the competition results themselves are not scientifically conclusive. But the process of competition, including the lessons learned, can be scientifically valuable.